Chapter 5 - Combustion Requirements Envelope

5. COMBUSTION REQUIREMENTS ENVELOPE

5.1 INTRODUCTION

The purpose of this section is to present a description of the combustion science requirements. This is a top-level description which is the intent of this document; more detailed discussions on the requirements are provided in supporting documents such as the individual Science Requirements Documents and hardware capabilities documents. This level of detail is intended to provide "envelope" requirements for necessary capabilities of use to most (if not all) experiments. The "envelopes" are defined in terms of selected detailed requirements from the “basis” (or reference) experiments described in Appendix B.

This section is organized in the sequence of a logical progression of steps in the process of performing an experiment:

- **Hypothesis:** The Principal Investigator proposes an hypothesis and supporting theoretical model of the phenomena to be investigated and defines the experiment(s) to be conducted in order to validate the hypothesis.
- **Definition:** Experiment definition involves establishing the experiment requirements, which include the experiment operating conditions and the experimental measurements to be made.
- **Execution:** The data obtained needs to be managed (i.e., recorded, tagged, and analyzed), and the results are compared with predictions of the theoretical model.

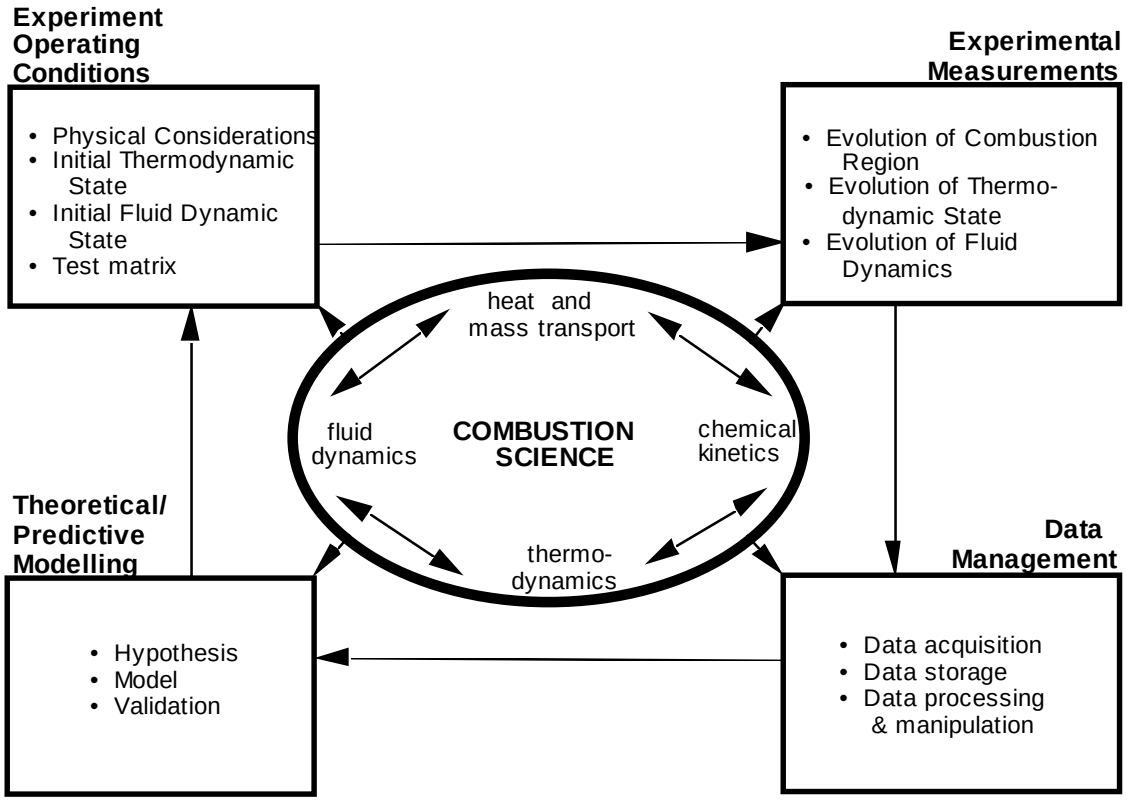
The scope of this section does not include theoretical modeling and data analysis, but focuses on the experimental aspect of the process. Hence, the following material is concerned primarily with experiment operating conditions and experimental measurements.

This section is divided into the following subsections:

- **Experiment Operating Conditions (Section 5.2)**: These are requirements on parameters which define the conditions in which the experiment is conducted.
- **Experiment Measurements (Section 5.3)**: These are requirements on parameters to be measured during the course of the experiment.
- **Data Management (Section 5.4)**: These are requirements on the acquisition and management of data acquired in the course of the experiment.

Facing figure shows a logical evolution of the experimental process which has been used to organize the requirements which follow.

EXPERIMENT PROCESS MODEL



5.2 EXPERIMENTAL OPERATING CONDITIONS

The requirements discussed in this section pertain to conditions under which experiments are to be conducted. This includes most of the physical bounds necessarily imposed by the FCF as well as the state of the sample prior to initiation of a combustion experiment.

The following parameters are presented below in terms of requirement "envelopes" which are defined in terms of the "basis" (or reference) experiments included in this document.

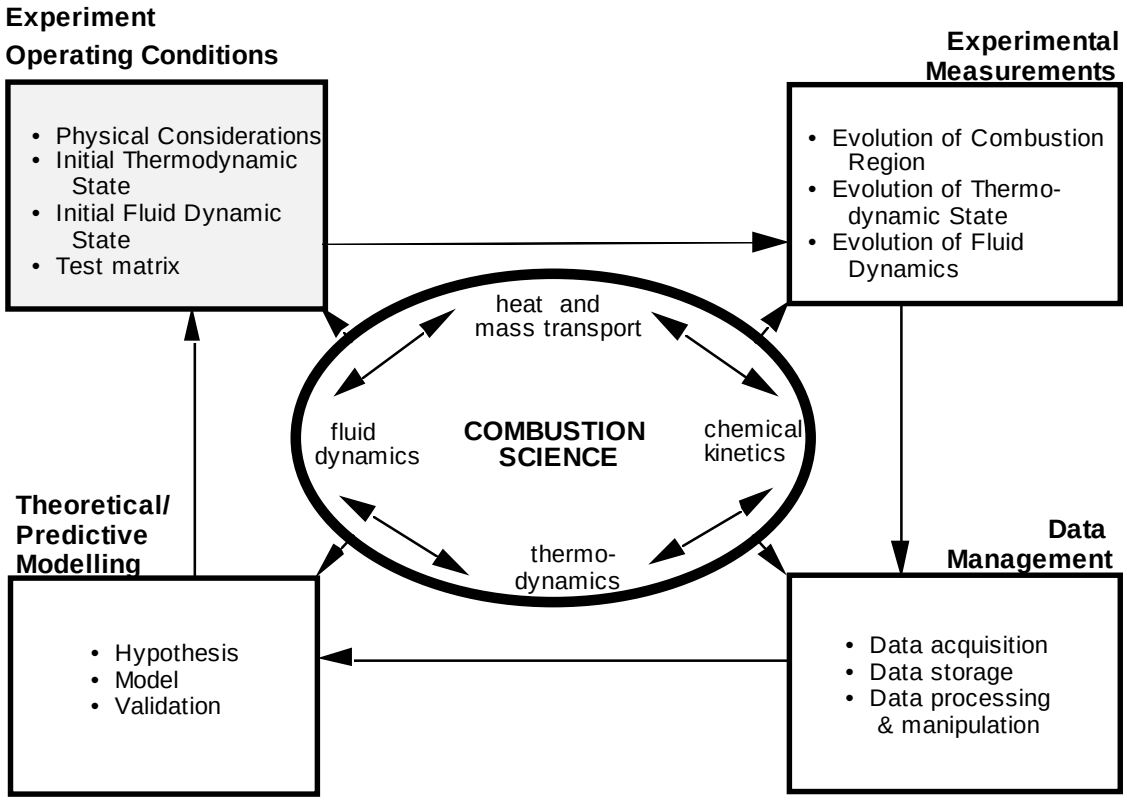
- **Physical Considerations (5.2.1)**: The FCF must provide the primary capabilities for containment, ignition, and local environment represented by the basis experiments.
- **Initial Thermodynamic State (5.2.2)**: The FCF must accommodate the range of temperatures, pressures, and compositions typical of modern combustion science.
- **Initial Fluid-Dynamics State (5.2.3)**: The FCF must accommodate the range of flow and gravitational acceleration conditions demanded by the basis experiments.
- **Test Matrix (5.2.4)**: The FCF must be scaled to accommodate the large data streams resulting from extended and repetitive experiments.

The following is a list of the requirements on operating conditions listed under the appropriate subsection. *Note: Requirement numbers are prefixed with a capital C to indicate that it is a Combustion requirement. Small letter c's in the requirement pictures (i.e., c1 through c11) indicate the combustion basis experiment number.*

- **5.2.1 - Physical Considerations**:
  - Requirement C1 - Test Section Dimensions
  - Requirement C2 - Initial Fuel State and Ignition Mechanisms
  - Requirement C3 - Acceleration and Vibration
- **5.2.2 - Initial Thermodynamic State**:
  - Requirement C4 - Pressure and Temperature
  - Requirement C5- Oxidizer Composition
- **5.2.3 - Initial Fluid-Dynamics State**:
  - Requirement C6 - Fluid Flow
- **5.2.4 - Test Matrix**:
  - Requirement C7 - Number and Duration of Tests

Facing figure illustrates the experimental process previously shown with the Experiment Operating Conditions (this Section 5.2) highlighted. All requirements related to these conditions are in this section.

EXPERIMENT PROCESS MODEL



5.2.1 Physical Considerations

Req. C1 - Test Section Dimensions

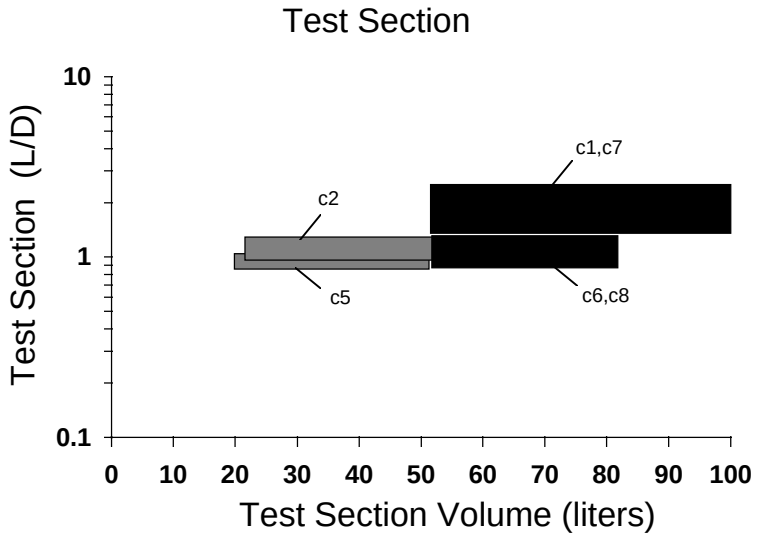
The FCF shall provide a combustion chamber with adequate volume and dimensions to accommodate the test sections of basis experiments C1 through C11.

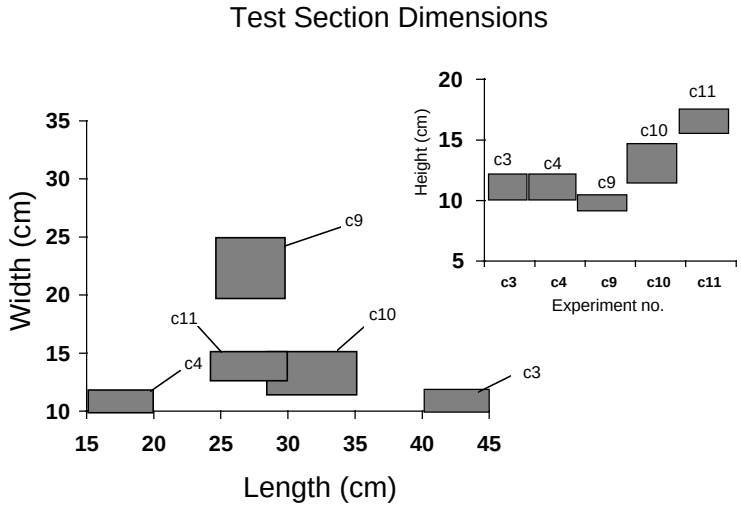
The "test section" refers to the physical volume where the combustion phenomena of interest is studied.

The requirements on test section dimensions are provided in terms of volume and the ratio of length (L) to diameter (D) for circular cross-sections (as in basis experiments c1, c2, c5, c6, c7, and c8). For noncircular cross-sections, the three major dimensions (length, width, and height) are provided.

The requirement on test section volume in some instances (e.g., c7) is driven by the need to limit oxygen consumption percentage. It may be acceptable to reduce the volume of the test section if a slow purge and resupply of fresh oxidizer is provided. For experiment c2, the test volume must be refilled with fresh mixture for each test point.

Facing figures show the distribution of test volumes and dimensions which define the envelope required to accommodate the basis experiments presented in this document.


Test Section
Test Section (L/D)
10
1
0.1
c1,c7
c2
c5
c6,c8
0
10
20
30
40
50
60
70
80
90
100
Test Section Volume (liters)


Test Section Dimensions
Width (cm)
35
30
25
20
15
10
c9
c11
c10
c4
c3
15
20
25
30
35
40
45
Length (cm)
Height (cm)
20
15
10
5
c3
c4
c9
c10
c11
Experiment no.

Req. C2 - Initial Fuel State and Ignition Mechanisms

The FCF shall provide a capability for storage, distribution and mixing of fuels and oxidizer. It shall also provide power and controls for igniting fuel/oxidizer mixtures using experiment provided igniter mechanisms. Fuels can be gaseous (e.g., hydrocarbons, alkenes and selected aromatics); liquid (e.g., alcohols and alkanes); or solid fuels (e.g., polymers, wood, cloth, and selected metals). Typical ignition mechanisms include hot wires and surfaces, sparks, and lasers.

The initial state of the fuel is important since it largely determines how the fuel is handled. The fuel may initially be in any of the three traditional states of matter: gas, liquid, or solid.

Gas fuel experiments require injectors and/or flame holders. The gaseous fuels called out in the basis experiments include hydrogen, methane, propane, ethylene, acetylene, propylene, and ethane. These may be mixed with diluents such as nitrogen, helium, noble gases, and sulfur hexafluoride.

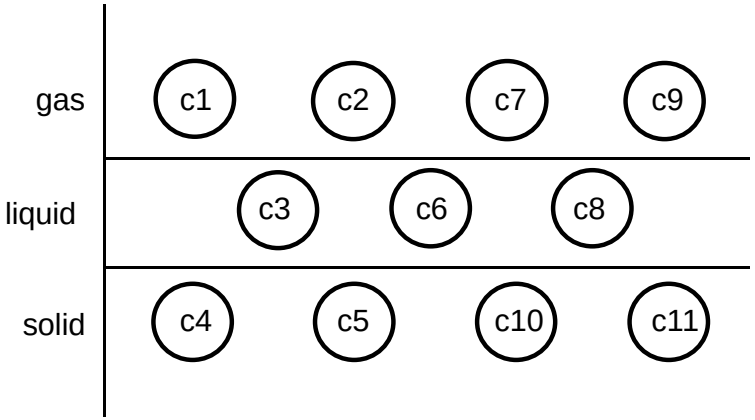
Liquid fuel experiments require containers, droplet injectors, and deployers. Liquid fuels called out in the basis experiments include propanol, butanol, n-decane, n-heptane, and methanol. Test mixtures may utilize more than one liquid fuel.

Solid fuel experiments require fuel sample holders. Solid fuels include ashless filter paper, polymethylmethacrylate (PMMA), polyurethane foam (non-flame retardant), wood, cloth, Velcro, cellulose powder, lycopodium powder, polydifluoroethylene (Teflon), polyimide (Kapton), coal, and metals.

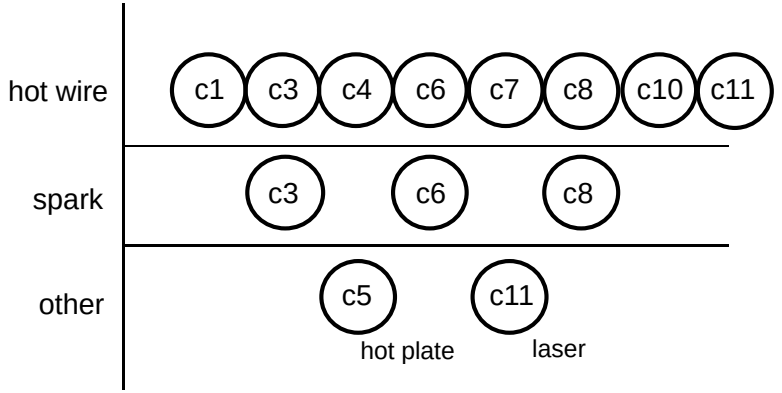
The purpose of the igniter mechanism is to initiate the combustion process in a reproducible manner. Ignition mechanisms are herein classified as hot wire, spark, or other. The geometry of the igniter is experiment dependent (e.g., for droplet combustion, the mechanism must maintain symmetry to minimize drop displacement). Ignition mechanisms classified as "other" include hot plates (surfaces) and focused optical sources (such as lasers).

Facing figures show the distribution of sample types and ignition methods within the basis experiments presented in this document.

Initial Fuel State



Fuel Ignition Mechanisms



Req. C3 - Acceleration and Vibration

The FCF shall provide an environment which minimizes the "quasi-steady state" accelerations, vibratory disturbances, and transient impulses.

The low-gravity (near "microgravity") environment of an orbiting laboratory provides the primary rationale for doing experiments in space. The "pure" environment of a simple, free-falling orbiting body can be disturbed (indeed, degraded) by three factors:

- quasi-steady accelerations exhibiting persistent direction or very low frequency (i.e., pseudo-dc) modulation due to off-sets from the center of gravity, vehicle drag characteristics, asymmetric orbits, etc.
- vibratory motions of structure and dynamics of a large, manned vehicle such as International Space Station, and
- impulse motions such as collisions during orbiter docking or impacts of hatches or doors, etc.

The acceleration environment in which experiments are conducted is extremely important in interpreting results. The requirements called out by the basis experiments are shown below in terms of normalized acceleration level as a function of frequency. The low frequency limits (nominally less than 1 Hz for this analysis) are of the order of the inverse of the burn time and may be construed as the quasi-steady acceleration levels required to assure "microgravity" behavior for the combustion phenomena of interest in the pertinent basis experiment.

It should be noted that effects of "g-jitter" (vibratory or unsteady acceleration levels) on combustion phenomena are not fully understood. The acceleration requirements for most experiments, exhibited below, were obtained by utilizing the quasi-steady level identified for each experiment and assuming a $1/\omega$ (ω is frequency) dependence of g-jitter induced velocity when flows are small. Thus, denoting the quasi-steady g-level as g_s, g-jitter requirements may be stated as follows:

$$\text{For } \omega < \omega_0 , \quad g' < \alpha g_s$$

$$\text{For } \omega > \omega_0 , \quad g' < (\omega - \omega_0)\, \alpha g_s + \alpha g_s$$

Here, ω_0 is a small value of ω where quasi-steady conditions are approximately satisfied and α is a number close to unity. For basis experiment c2, the acceleration requirements are:

$$\text{For } \omega < 2\text{Hz}, \quad g' \leq 1 \quad 4 \times 10^{-4} g_0$$

$$\text{For } \omega > 2\text{Hz}, \quad g' \leq 10^{-4} \times \omega^2 \, g_0$$

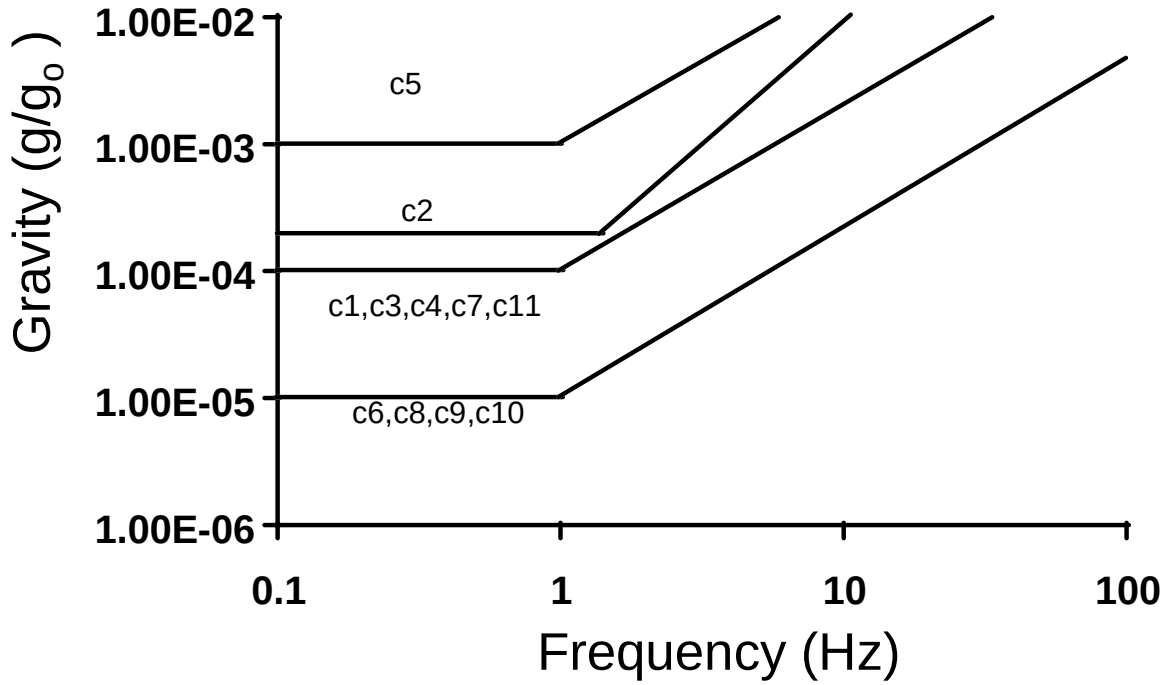
Where g_0 is the standard value of normal gravity acceleration.

Des. DC1

It is desirable to have a quasi-steady acceleration level of $10^{-6} g_0$ during conduct of the experiments.

Facing figure shows the distribution of the upper bounds for quasi-static and vibratory excitation called out for selected basis experiments. It should be noted that these all reside within the bounds called out in SSP 4100D.

Acceleration Requirements



5.2.2 Initial Thermodynamic State

Req. C4 - Pressure and Temperature

The FCF shall provide pressure containment and control for initial gas pressures in the range of 0.02 to 3 atmosphere and initial gas temperatures of 268 to 320°K. Condensed phase fuel temperatures shall be controllable to ±1°K in the range 268 to 315°K.

The initial conditions of pressure and temperature, in conjunction with chemical composition, determine the initial thermodynamic state. Requirements on initial test section pressure and temperature identified in the basis experiments are shown below. The oxidizer temperature range is to be considered representative of the gas-phase temperature (e.g., in basis experiment c2, the gas phase is a mixture of both oxidizer and fuel components).

For experiments using a condensed phase fuel (solid or liquid), the requirement implies that oxidizer and fuel temperatures are nominally the same. For experiment c3, the restrictions on allowable temperatures depend upon the fuel and these determine the combustion regime (i.e., pulsating versus steady flame spread). Thus, for this experiment, the fuel and oxidizer temperature may need to be controlled depending upon the Space Station ambient conditions.

The range in initial oxidizer and fuel temperature for the other experiments reflects the tolerance on variation from standard temperature conditions allowable.

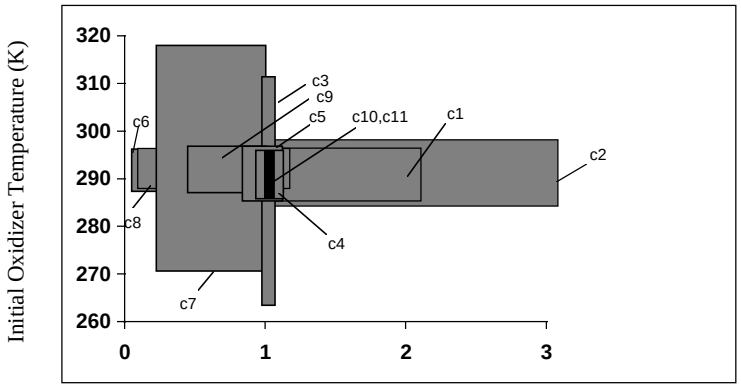
In some instances (not included in these basis experiments), pressure requirements may range in excess of 100 atm. These experiments will require considerably smaller volumes than in current concepts for the Test Section (on the order of 8 liters).

It is also to be noted that as a result of the combustion process, the pressure can exceed the initial value during or at the conclusion of the test.

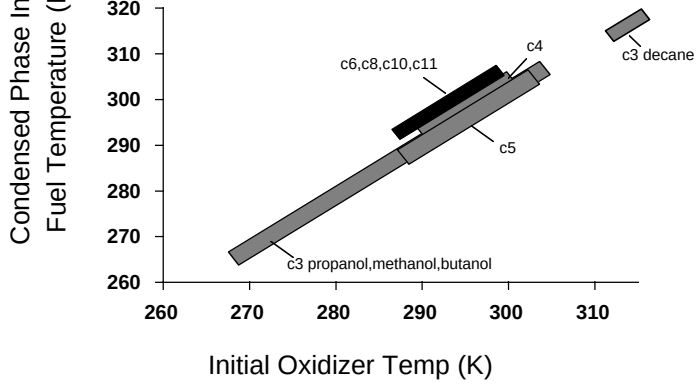
Temperature control of test section components, including the walls and burner assembly, may be required in some experiments. The cooling rate will not, in general, exceed the heat release rate from the combustion phenomena. These rates range from a few watts for weak flames to approximately 2KW for more vigorous flames.

Facing figures show the distribution of initial temperatures and pressures which define the envelope required to accommodate the basis experiments presented in this document.

Operating Conditions in Pressure and Temperature



Operating Conditions in Pressure and Temperature



Req. C5 - Oxidizer Composition

The FCF shall provide oxidizer, which will generally be a mixture of oxygen and one or more diluents. Oxygen concentration in this mixture will vary over the range of 0 to 70%.

The combustion characteristics are strongly dependent upon the oxygen concentration, as well as the nature and amount of diluents. The concentration ranges shown below are expressed in terms of volume percent of diluent and oxygen. The sum of the respective volumes must be 100% (several bars plotted below are offset for clarity). However, for premixed flames, the fuel is also mixed with the oxidizer and these systems are not reflected in the graph.

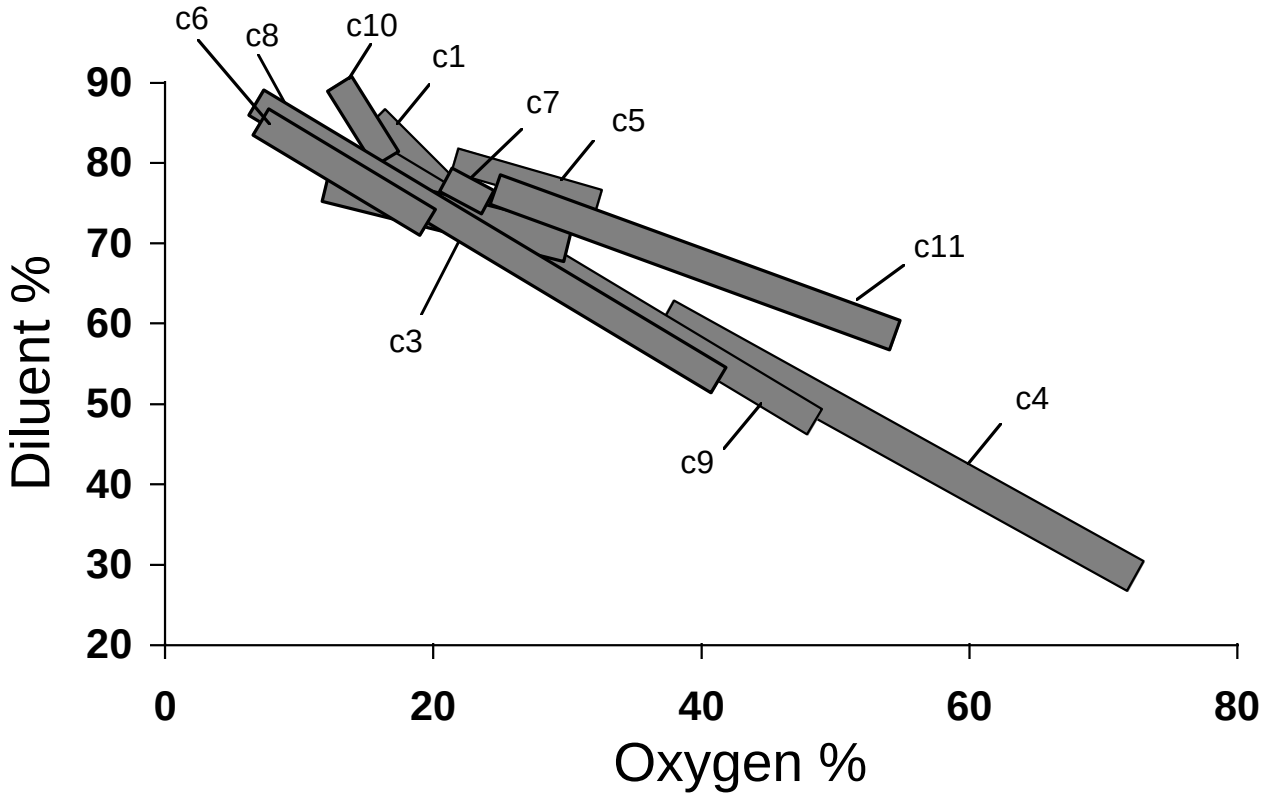
Diluents may include N_2, CO_2, Ar, He, SF_6, Xe, and other noble gases.

Des. DC2

It is desirable to have the ability to burn in a 100% oxygen environment.

Facing figure shows the distribution of oxidizer and diluent concentrations which define the envelope required to accommodate the basis experiments (non-premixed cases) presented in this document. Note that for visual clarity, the requirements for the different experiments are offset from each other.

Oxidizer Composition and Flow



5.2.3 Initial Fluid Dynamics State

Req. C6 - Fluid Flow

The FCF shall provide controlled flow of fuel over the volume flow rate range of 0 to 30 cc/sec under standard conditions (i.e., scc/sec) and controlled flow of oxidizer over the volume flow rate range of 0 to 4,000 scc/sec.

This requirement deals with the initial flow of gases through the experiment test section. The graph below displays these initial flow rates for both oxidizer and fuel flows.

In some experiments, the fuel may be flowing and the oxidizer is initially stationary, and vice-versa. In general, flowing fuel would be in the gaseous state; however, in some instances, condensed phase fuel samples may be translated relative to the oxidizer.

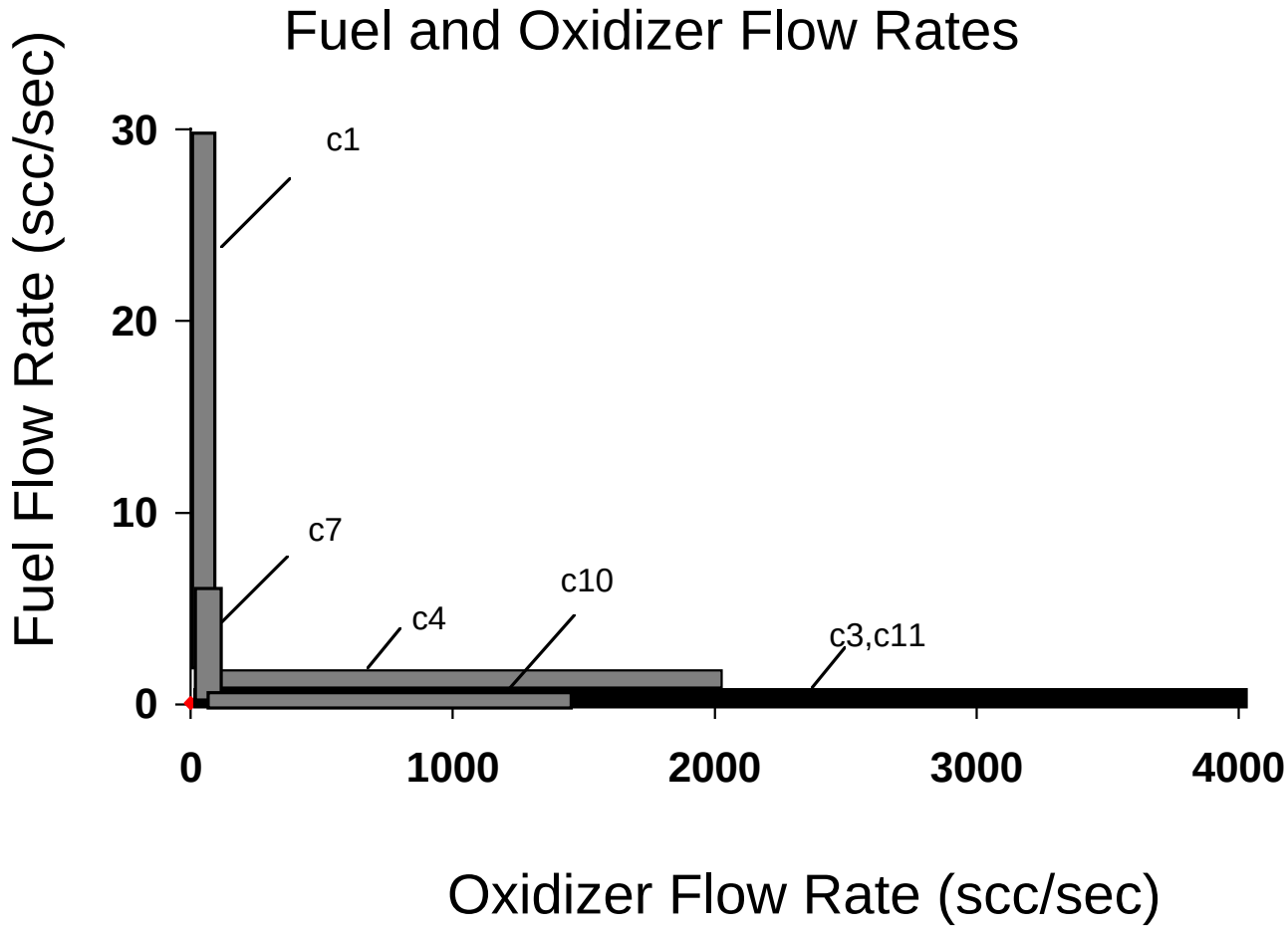
In some cases, e.g., c3, it may be acceptable to utilize a recirculating flow; however, the flow-through capability must be maximized to the extent possible.

The graph does not contain information on the flow of premixed fuel and oxidizer.

Des. DC3

It is extremely desirable to have the capability to flow premixed fuel and oxidizer through the test section in a controlled manner. Such experiments cannot utilize a recirculating flow. Overall (fuel and oxidizer) flow rates may range to 4,000 scc/sec.

Facing figure shows the distribution of oxidizer and fuel flow rates which define the envelope required to accommodate the basis experiments presented in this document.


Fuel and Oxidizer Flow Rates
Fuel Flow Rate (scc/sec)
30
20
10
0
c1
c7
c10
c4
c3,c11
0
1000
2000
3000
4000
Oxidizer Flow Rate (scc/sec)

5.2.4 Test Matrix

Req. C7 - Number and Duration of Tests

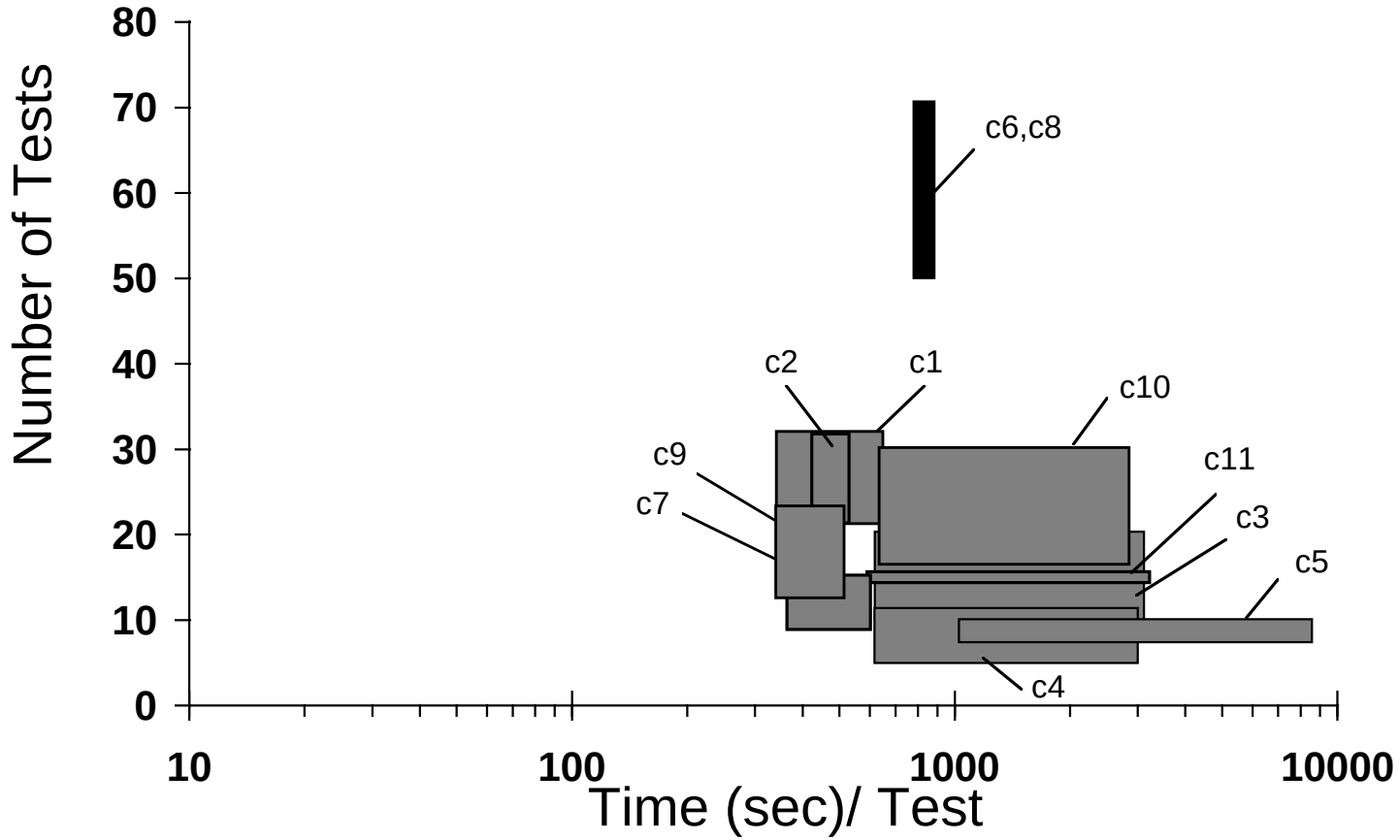
The FCF shall provide all necessary support (e.g., data storage, fuel, oxidizer, and diluent storage and distribution, combustion product collection and disposal) to accomplish experiments having ranges of duration and repetition represented by the basis experiments described in this document.

The number of tests displayed on the graph below is an estimate of the number of different, successful test points required to validate the hypotheses of the experiment and obtain definitive data.

The time per test includes time for preburn operations associated with the test point. Examples of these operations include liquid fuel deployment in the experiment container (e.g., for c3) and droplet deployment and stretching (e.g., for c6 and c8). Many of these pre-burn operations require the reduced-gravity environment.

Facing figure shows the distribution of test times and number of tests which define the envelope required to accommodate the basis experiments presented in this document.

Estimates of Number of Tests and Test Times



5.3 EXPERIMENTAL MEASUREMENTS

The requirements discussed in this section pertain to measurements that must be performed in the course of most combustion experiments.

The following parameters are presented below in terms of requirement "envelopes" which are defined in terms of the basis experiments included in this document:

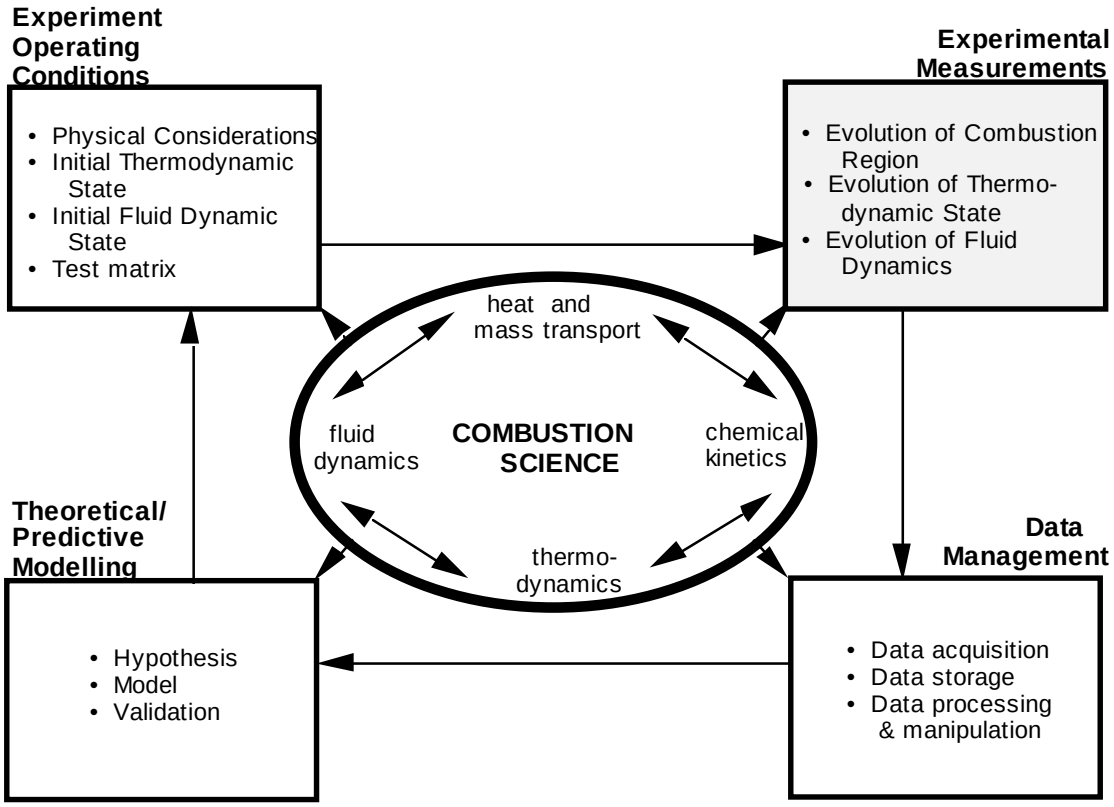
- **Evolution of the Combustion Region (5.3.1)**: The FCF provides power, control and data acquisition capabilities for imaging and optical measurement.
- **Evolution of the Thermodynamic State (5.3.2)**: The FCF provides power, control and data acquisition capabilities for measurement of the range of temperatures, pressures, and compositions occurring in the combustion process.
- **Evolution of the Fluid-Dynamics (5.3.3):** The FCF provides power, control and data acquisition capabilities for measurement of dynamic flow and acceleration environments during experiment operation.

The following is a list of the requirements on experimental measurements listed under the appropriate subsection. Suggestions on diagnostic techniques are also indicated. *Note: Requirement numbers are prefixed with a capital C to indicate that it is a Combustion requirement. Small letter c's in the requirement pictures (i.e., c1 through c11) indicate the **c**ombustion experiment number.*

- **5.3.1 - Evolution of the Combustion Region**:
  - Req. C8 - Visible Imaging
  - Req. C9 - IR Imaging
  - Req. C10 - UV Imaging
- **5.3.2 - Evolution of the Thermodynamic State**:
  - Requirement C11 - Temperature Point Measurements (gas phase)
  - Requirement C12 - Temperature Point Measurements (condensed phase)
  - Requirement C13 - Temperature Field Measurements (gas phase)
  - Requirement C14 - Temperature Field Measurements (condensed phase)
  - Requirement C15 - Pressure Measurements
  - Requirement C16 - Chemical Composition (including soot measurements)
  - Requirement C17 - Radiometry
- **5.3.3 - Evolution of the Fluid-Dynamics**
  - Requirement C18 - Velocity Point Measurements
  - Requirement C19 - Full field Velocity Imaging
  - Requirement C20 - Acceleration Measurements

Facing figure illustrates the experimental process previously shown with the Experimental Measurements (this Section 5.3) highlighted. All requirements related to these measurements are in this section.

EXPERIMENT PROCESS MODEL



5.3.1 Evolution of the Combustion Region

Req. C8 - Visible Imaging

The combustion element shall provide power, control and data acquisition capabilities for imaging in the visible spectrum (400-700 nm). The imaging systems shall accommodate the envelopes of parameters defined for the basis experiments. Framing rates to 100/sec are required.

Images of the combustion region in the visible spectrum provide information on flame shape and flame spread. For droplet combustion studies, the images also serve to track the droplet diameter as a function of time.

Important parameters associated with these images are field of view, depth of field, spatial resolution, and framing rate. The ranges of these parameters required for the basis experiments are displayed in the following graphs and serve to define "envelopes." The "axial" direction refers to the direction of flame propagation or fuel flow.

Color imaging is required for most of the basis experiments. Orthogonal or near-orthogonal views are required for some cases to verify the symmetric nature of the flame, or to obtain different views of the combustion phenomena.

Back lighting is required for the droplet combustion experiments to enable tracking of droplet diameter. The imaging system must account for droplet drift perpendicular to the imaging plane.

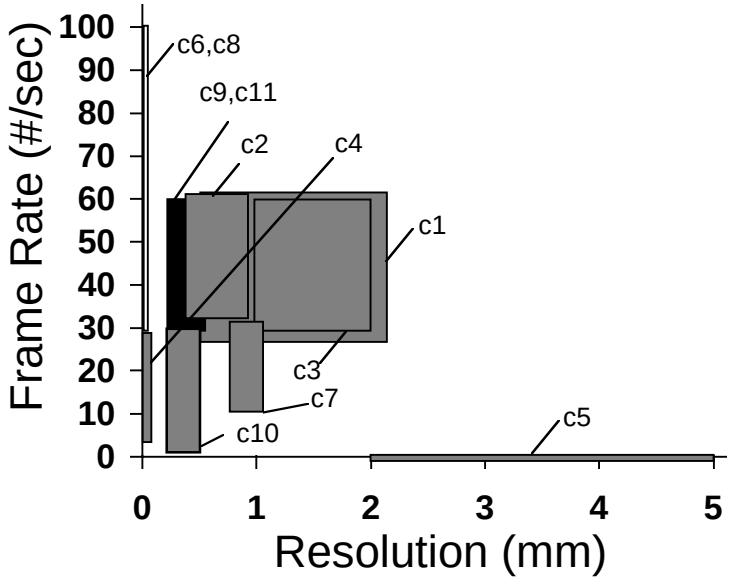
Des. DC4

It is desirable to accommodate framing rates to 1,000/sec.

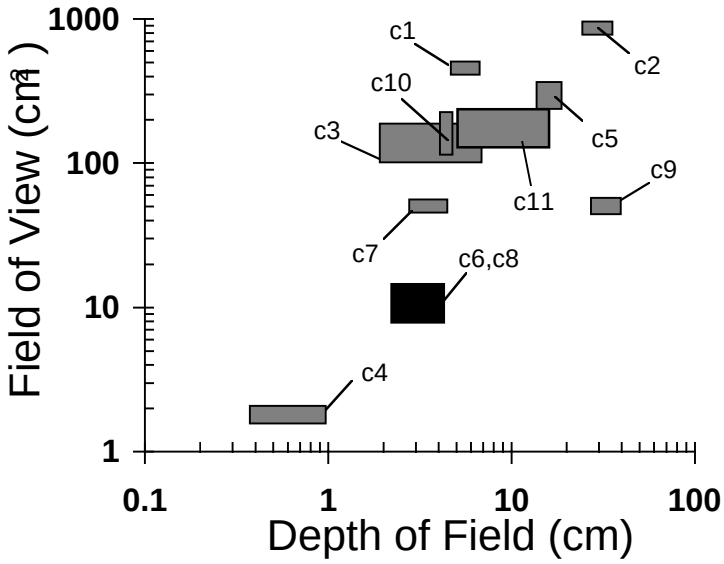
Suggested Techniques: High resolution, low light sensitive, color, and black and white video cameras. These may require band pass filtering with RGB filters and subsequent recombination to obtain color composite images.

Facing figures show the distribution and range of parameters for resolution, frame rate, field of view, and depth of field for visible imaging which define the envelope required to accommodate the basis experiments presented in this document. An additional figure is on the following pages.

Visible Imaging



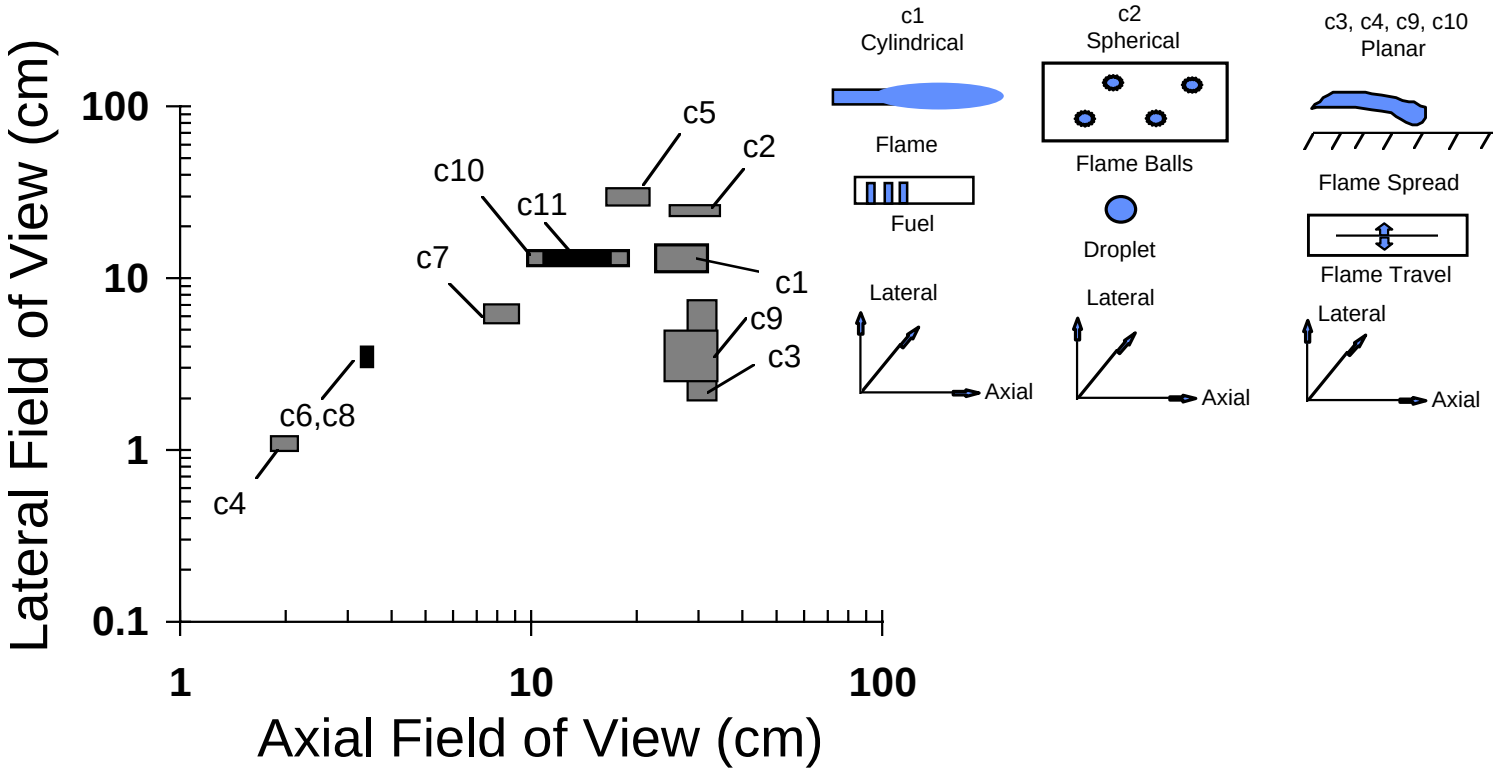
Visible Imaging



Req. C8 - Visible Imaging (cont.)

Facing figure shows the distribution and range of parameters of lateral and axial field of view for visible imaging which define the envelope required to accommodate the basis experiments presented in this document.

Visible Imaging



Req. C9 - IR Imaging

The FCF shall provide power, control and data acquisition capabilities to image flames and surfaces in the infrared spectrum in the wavelength range of 1,000 to 5,000 nm and 8,000 to 14,000 nm. Framing rates to 60/sec are required.

Images of the combustion region at wavelengths in the infrared spectrum provide information about the spatial distribution of combustion species concentration and temperature. Two wavelength ranges are of primary interest: 1,000 to 5,000 nm and 8,000 to 14,000 nm. When the surface of condensed phases are viewed, the surface temperature can be inferred from knowledge of the surface emittance.

Important parameters associated with these images are field of view, depth of field, spatial resolution, and framing rate. The ranges of these parameters required for the basis experiments are displayed in the following graphs and serve to define "envelopes." The "axial" direction refers, again, to the direction of flame propagation or fuel flow.

When the infrared imager is used primarily as a temperature sensor, additional requirements apply (see Requirements C13 and C14, Temperature Field Measurements).

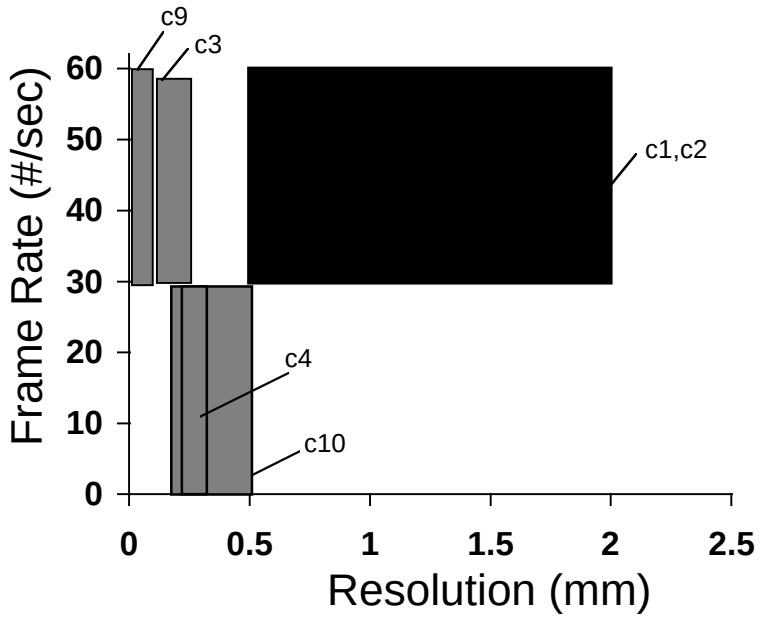
Des. DC5

It is desirable to accommodate framing rates to 1,000/sec.

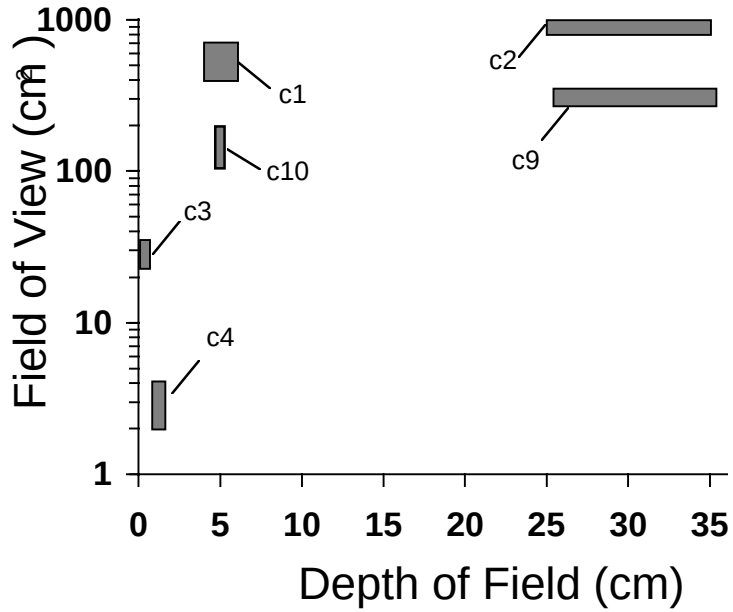
Suggested Techniques: High resolution infrared cameras with imaging wavelengths in the 1,000 to 5,000 nm and 8,000 to 14,000 nm ranges.

Facing figures show the distribution and range of parameters for resolution, frame rate, field of view, and depth of field for infrared imaging which define the envelopes required to accommodate the basis experiments presented in this document. An additional figure is on the following page.

IR Imaging



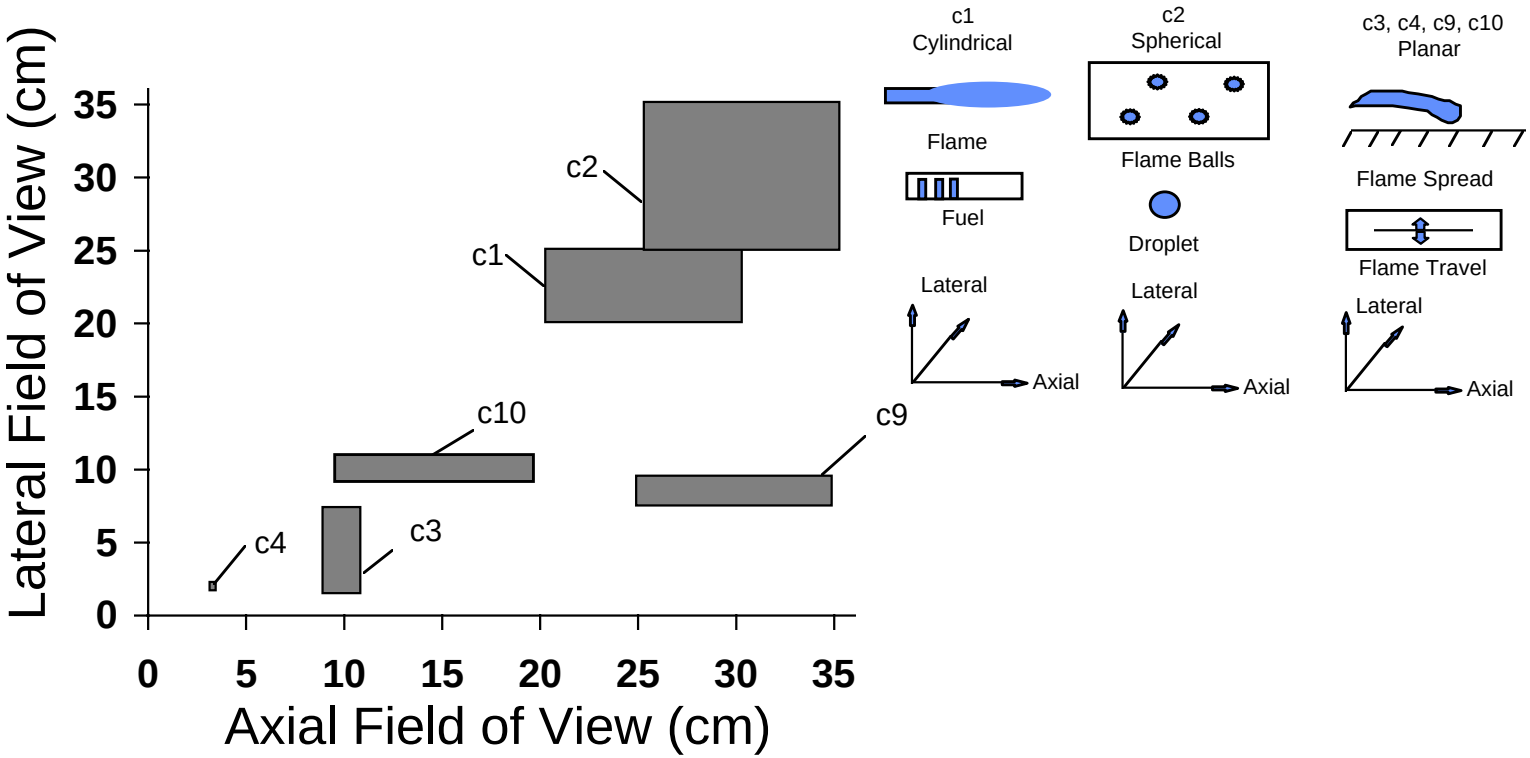
IR Imaging



Req. C9 - IR Imaging (cont.)

Facing figure shows the distribution and range of parameters of lateral and axial field of view for infrared imaging which define the envelope required to accommodate the basis experiments presented in this document.

IR Imaging


Lateral Field of View (cm)
0
5
10
15
20
25
30
35
Axial Field of View (cm)
c1
c2
c3
c4
c9
c10
c1
Cylindrical
Flame
Fuel
Lateral
Axial
c2
Spherical
Flame Balls
Droplet
Lateral
Axial
c3, c4, c9, c10
Planar
Flame Spread
Flame Travel
Lateral
Axial

Req. C10 - UV Imaging

The FCF shall provide power, control and data acquisition capabilities for imaging in the ultraviolet spectrum (nominally 250 to 400 nm). Framing rates to 100/sec are required.

Images of the combustion region in the ultraviolet spectrum provide information on the spatial distribution of the hydroxyl radical, OH, which emits at 310 nm. This image serves to define the reaction region of the flame.

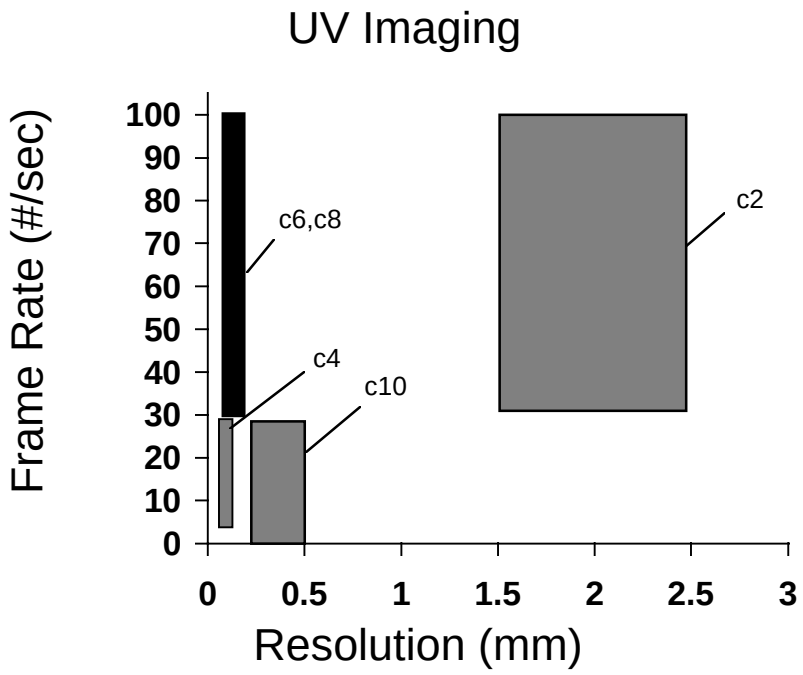
As above, important parameters associated with these images are field of view, depth of field, spatial resolution, and framing rate. The ranges of these parameters required for the basis experiments are displayed in the following graphs and serve to define envelopes. The "axial" direction refers, again, to the direction of flame propagation or fuel flow.

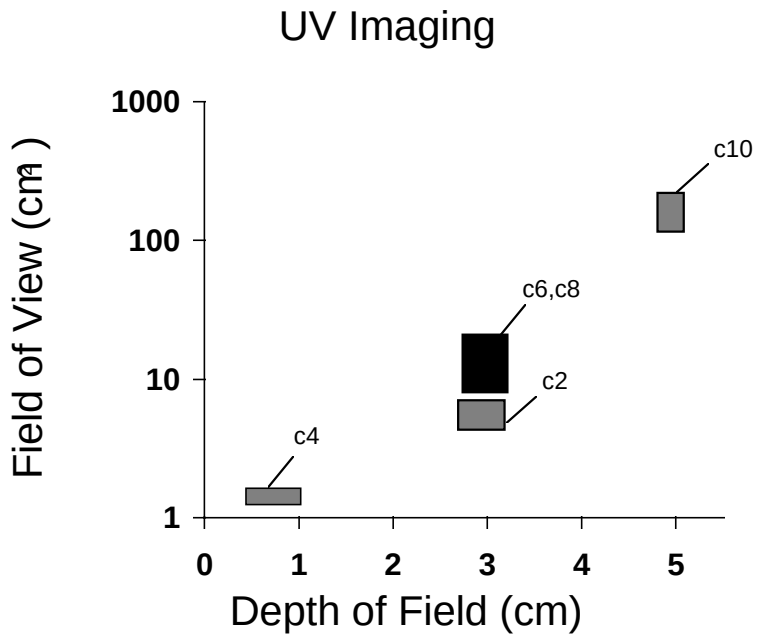
Des. DC6

It is desirable to accommodate framing rates to 1,000/sec.

Suggested Techniques: High resolution intensified imagers with imaging wavelenths in the range of 250 to 400 nm. Extended wavelength range intensified imagers may also be utilized for imaging in the visible spectrum as noted for Req. C8.

Facing figures show the distribution and range of parameters for resolution, frame rate, field of view, and depth of field for ultraviolet imaging which define the envelopes required to accommodate the basis experiments presented in this document. An additional figure is presented on the following page.

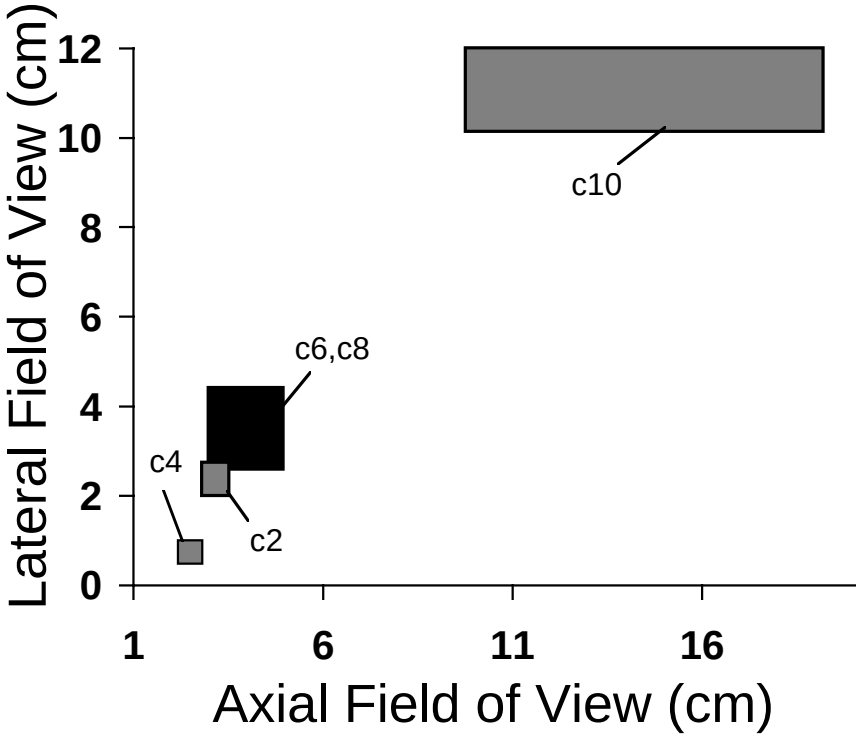

UV Imaging
Frame Rate (#/sec)
100
90
80
70
60
50
40
30
20
10
0
c6,c8
c4
c10
c2
0
0.5
1
1.5
2
2.5
3
Resolution (mm)

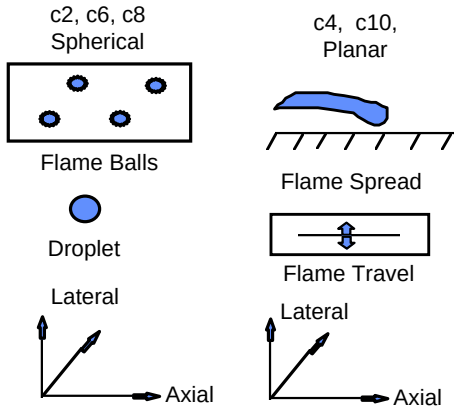

UV Imaging
Field of View (cm)
1000
100
10
1
c10
c6,c8
c2
c4
0
1
2
3
4
5
Depth of Field (cm)

Req. C10 - UV Imaging (cont.)

Facing figure shows the distribution and range of parameters of lateral and axial field of view for ultraviolet imaging which define the envelope required to accommodate the basis experiments presented in this document.

UV Imaging


Lateral Field of View (cm)
12
10
8
6
4
2
0
1
6
11
16
Axial Field of View (cm)
c10
c6,c8
c4
c2


c2, c6, c8
Spherical
Flame Balls
Droplet
Lateral
Axial
c4, c10,
Planar
Flame Spread
Flame Travel
Lateral
Axial

5.3.2 Evolution of the Thermodynamic State

Req. C11 - Temperature Point Measurements

The FCF shall provide power, control and data acquisition capabilities for making multi-point temperature measurements in the gaseous and condensed phases during the course of experiment operations. Up to 12 temperature measurements in the gas phase and up to 20 temperature measurements in the condensed phase are required. Measurements shall be sampled at selectable rates to 1,000 samples per second in the gas phase and to 30 samples per second in the condensed phase. The temperatures in the gas phase range from 280 to 2,000°K and, in the condensed phase, range from 200 to 1,100°K.

Point measurements of temperature in the gas phase provide spatially and temporally-resolved information on heat generation and heat transfer during the combustion process. Measurements are made in the flame region and outside the combustion zone.

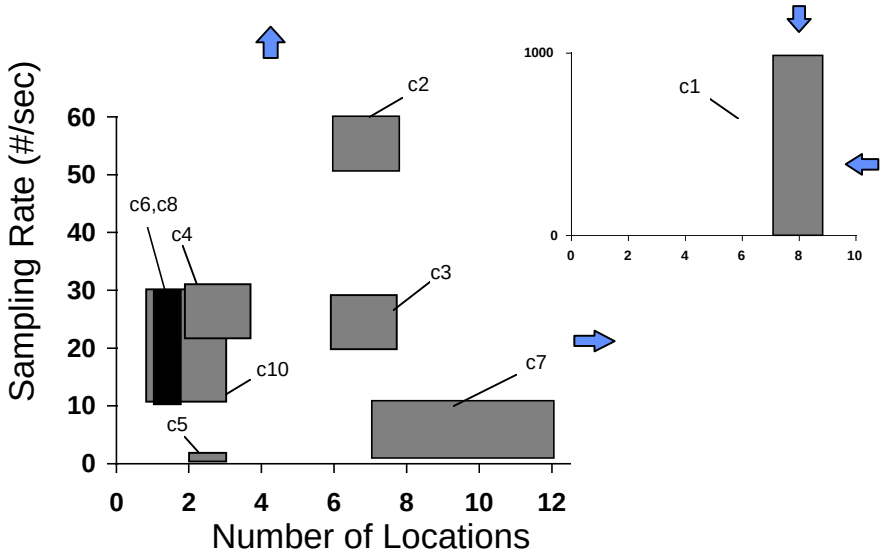
Point measurements of temperature in the condensed phase provide spatially and temporally resolved information on heat generation and heat transfer during the combustion process. Measurements are made on the surface of the fuel and at in-depth locations to obtain conduction rates.

Important parameters associated with these measurements include number of sensor locations, sampling rate, temperature range, and measurement accuracy. The ranges of these parameters required by the basis experiments are displayed in the following graphs and serve to define envelopes for this requirement.

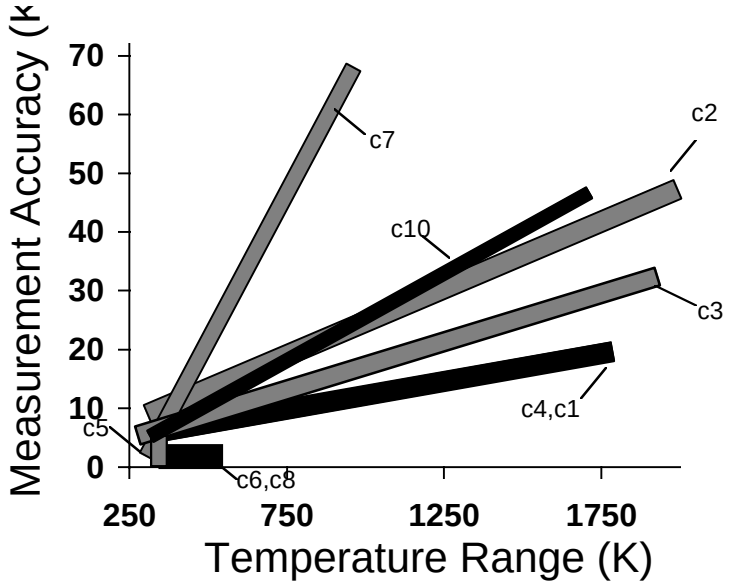
Suggested Techniques: Thermocouples, thermistors, SiC fibers, and Rayleigh scattering techniques. Fine-wire thermocouples may be used for high sampling rates in the gas phase (on the order of several hundred Hz) when flow rates are of sufficient magnitude provided their time constants are measured

Facing figures show the distribution and range, of parameters for number of sensor locations, sampling rate, temperature range and measurement accuracy for multi-point temperature measurement in the gas phase which define the envelopes required to accommodate the basis experiments presented in this document.

Gas - Phase Temperature - Point Measurements



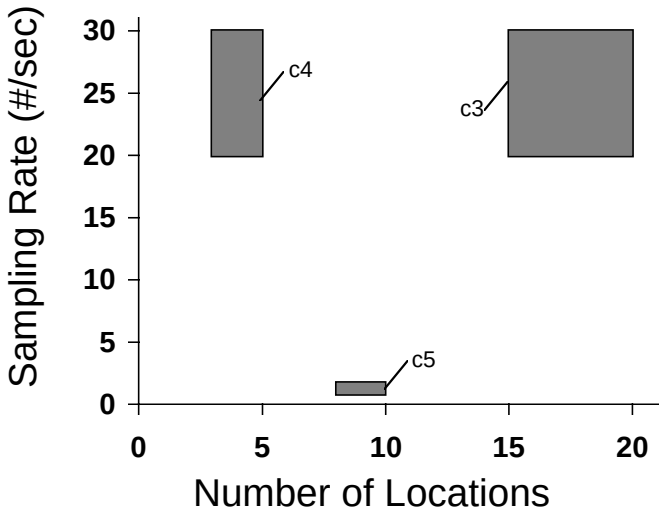
Gas - Phase Temperature - Point Measurements



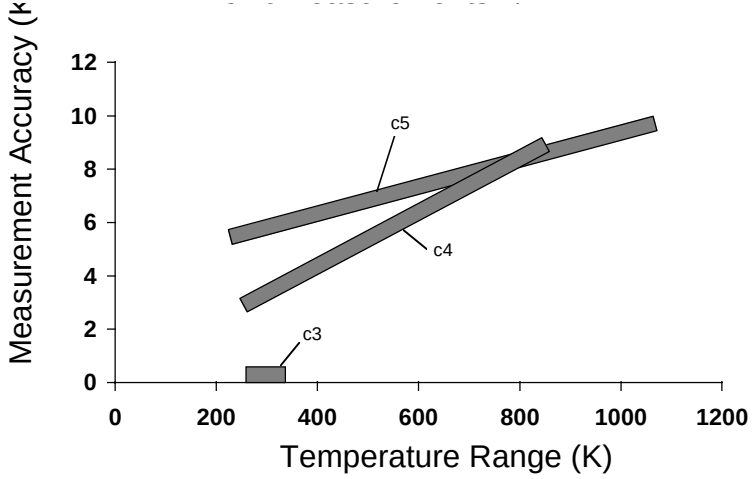
Req. C11 - Temperature Point Measurements (cont.)

Facing figures show the distribution and range of parameters for number of sensor locations, sampling rate, temperature range, and measurement accuracy for multi-point temperature measurement in condensed phases which define the envelopes required to accommodate the basis experiments presented in this document.

Condensed - Phase Temperature - Point Measurements



Condensed - Phase Temperature - Point Measurements



Req. C12 - Temperature Field Measurements

The FCF shall provide power, control and data acquisition capabilities for measuring temperature fields in the gaseous and condensed phases during the combustion experiment operations. Temperature fields may span the range 280 to 2,000°K in the gas phase and 280° to 350°K in the condensed phase. Sample rate shall be selectable to at least 60 samples/second.

Field measurements of temperature enable tracking of the spatial development of temperature with time and provide information on the heat generation and heat transfer caused by the combustion process.

Important parameters associated with these measurements are field of view, sampling rate, temperature range, and temperature resolution. The ranges of these parameters required for the basis experiments are displayed in the following graphs and serve to define envelopes.

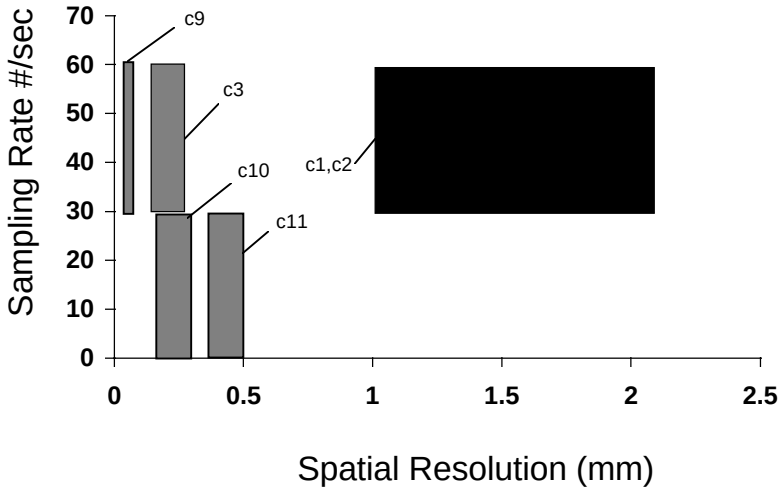
Des. DC7

It is desirable to accommodate sampling rates to 1,000 samples/second.

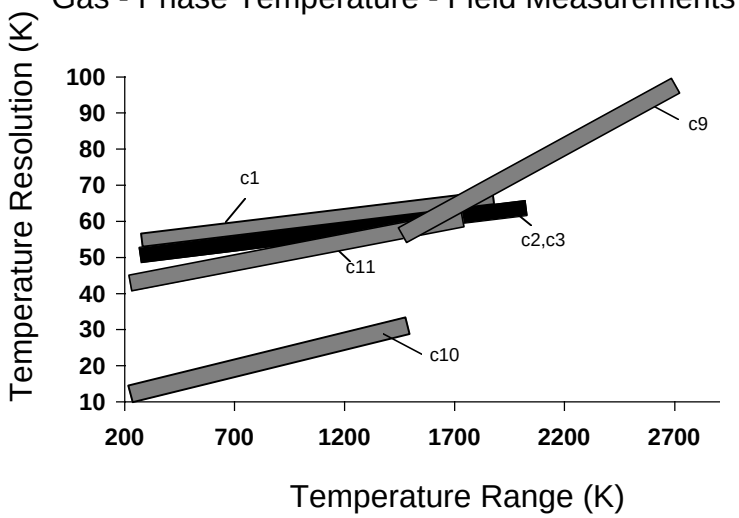
Suggested Techniques: Schlieren (regular and rainbow), shadowgraphy, interferometry, IR imaging.

Facing figures show the distribution and range of parameters for spatial resolution, sampling rate, temperature resolution, and temperature range for temperature-field measurement in gas phases which define the envelopes required to accommodate the basis experiments presented in this document. An additional figure is also provided on the following pages.

Gas - Phase Temperature - Field Measurements

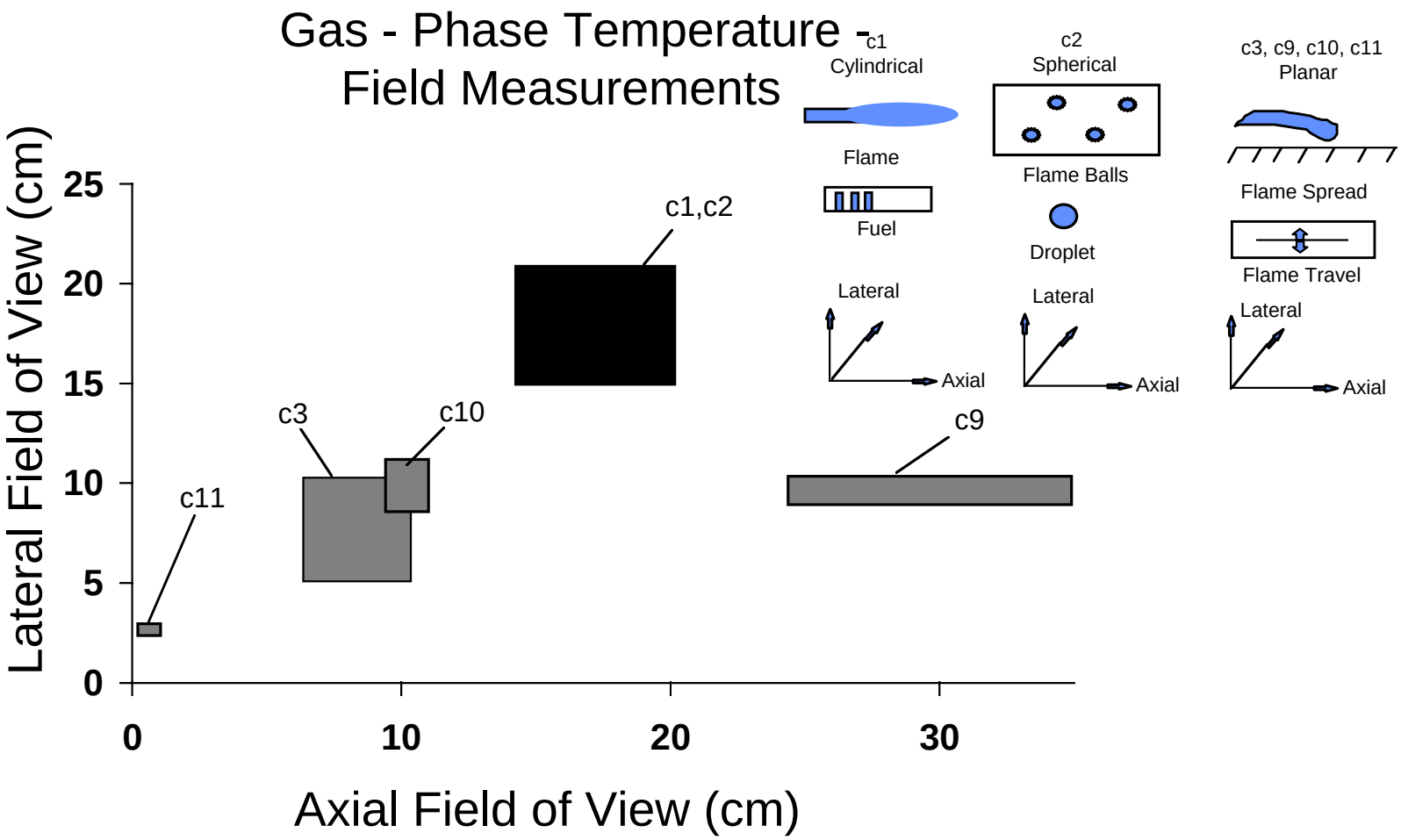


Gas - Phase Temperature - Field Measurements



Req. C12 Temperature Field Measurements (cont.)

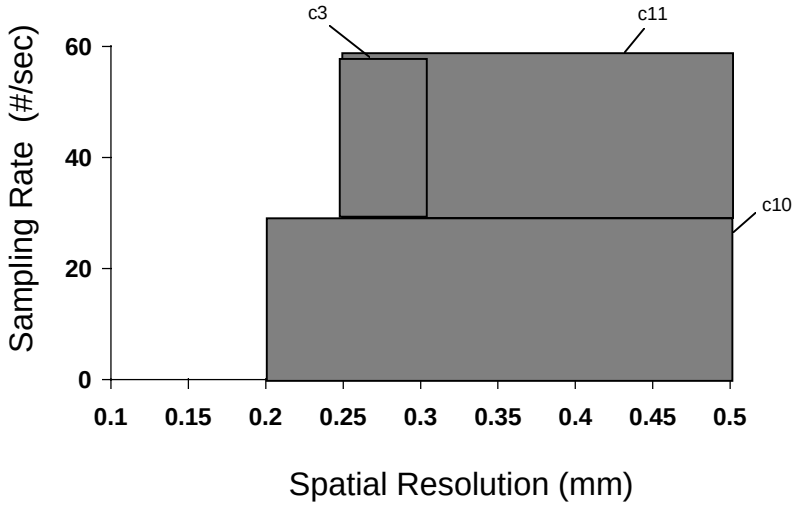
Facing figure shows the distribution and range of parameters of lateral and axial field of view for gas-phase temperature-field measurements which define the envelope required to accommodate the basis experiments presented in this document.


Gas - Phase Temperature -
Field Measurements
Lateral Field of View (cm)
25
20
15
10
5
0
0
10
20
30
Axial Field of View (cm)
c1,c2
c3
c10
c9
c11
c1
Cylindrical
Flame
Fuel
Lateral
Axial
c2
Spherical
Flame Balls
Droplet
Lateral
Axial
c3, c9, c10, c11
Planar
Flame Spread
Flame Travel
Lateral
Axial

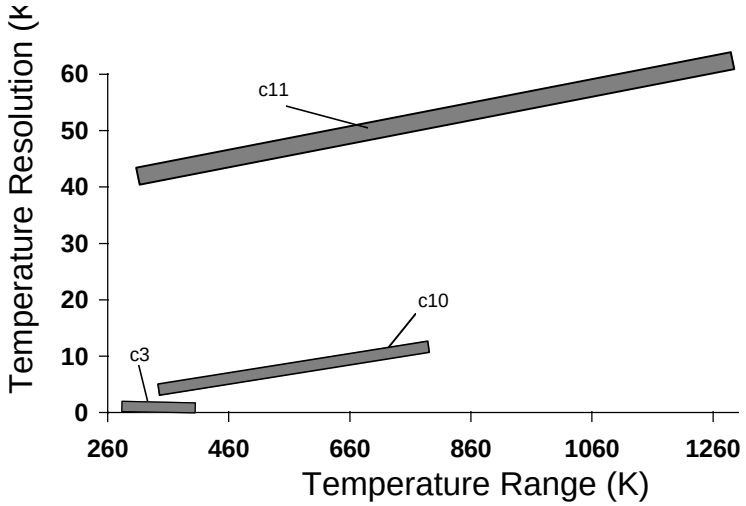
Req. C12 - Temperature Field Measurements (cont.)

Facing figures show the distribution and range of parameters for spatial resolution, sampling rate, temperature resolution, and temperature range for temperature-field measurement in condensed phases which define the envelopes required to accommodate the basis experiments presented in this document. An additional figure is also provided on the following pages.

Condensed Phase Temperature Field Measurements



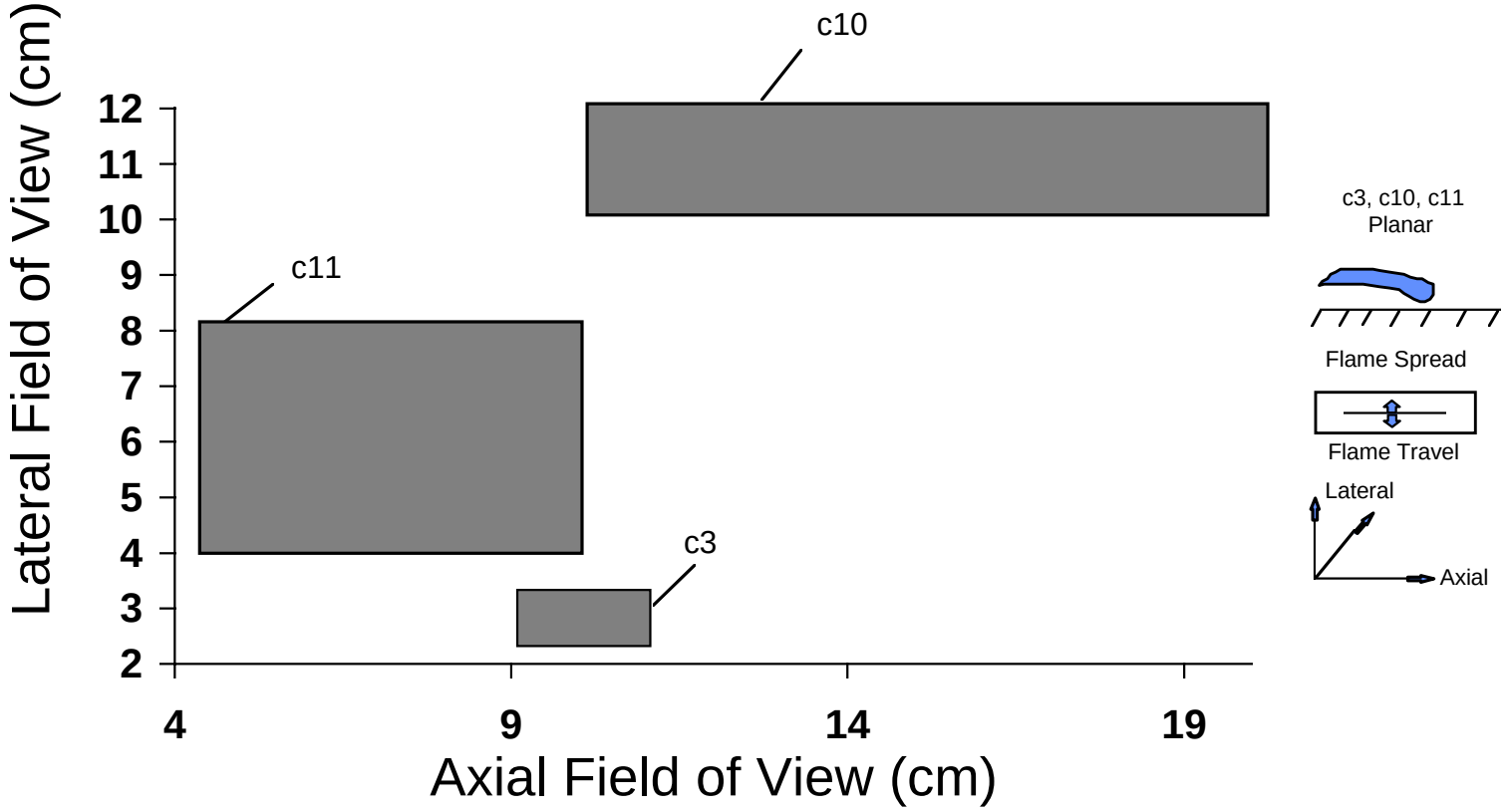
Condensed Phase Temperature Field Measurements



Req. C12 - Temperature Field Measurements (cont.)

Facing figure shows the distribution and range of parameters of lateral and axial field of view for condensed phase temperature-field measurements (see discussion below) which define the envelope required to accommodate the basis experiments presented in this document.

Condensed Phase Temperature Field Measurements



Req. C13 - Pressure Measurements

The FCF shall provide power, control and data acquisition capabilities for measuring pressure of the test section during the course of experiment operations. Pressures may span the range 0 to 10 atm.

Changes in pressure serve to track the progress of the combustion event. The pressure measurement requirements for the existing basis experiments track, primarily, the pressure changes in the test section.

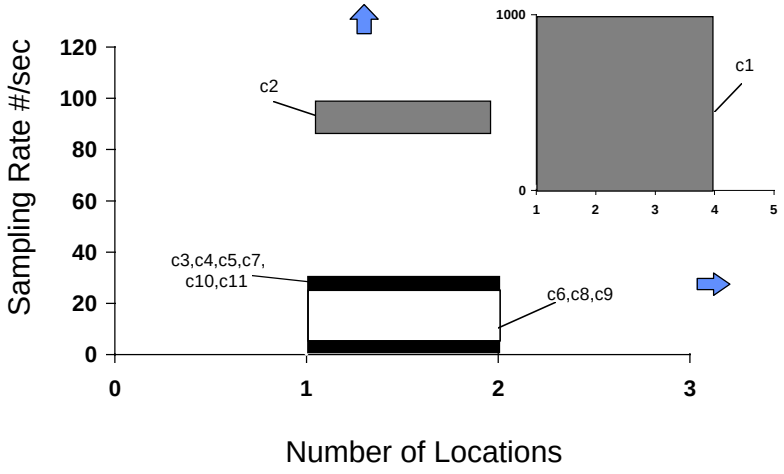
For experiments which can be carried out in smaller volumes, pressures may span to the range 100 to 150 atm.

The capability to measure both time-averaged and time-dependent pressure must be available. Hence, sample rates shall be selectable to at least 1,000 samples/second. This range will also enable tracking of acoustic phenomena.

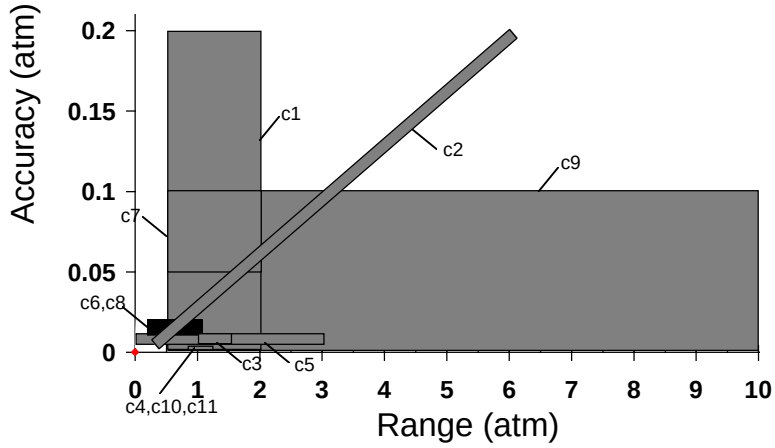
Suggested Techniques: Pressure transducers, condenser microphones.

Facing figures show the distribution and range of parameters for number of sensors, pressure range, and resolution for pressure measurement which define the envelopes required to accommodate the basis experiments presented in this document.

Pressure Measurements



Pressure Measurements



Req. C14 - Chemical Composition (including soot measurements)

The combustion element shall provide power, control and data acquisition capabilities for measuring chemical composition which includes gas sampling, gas analysis, soot volume fraction and distribution, soot temperature, and for collecting soot particles in the test section during the combustion experiment.

Information provided by chemical composition measurements include completeness of the combustion reactions, chemical kinetic mechanisms, and radiative heat transfer.

Gas analysis shall be feasible for the following components: water, low molecular weight alcohols, ketones, and hydrocarbons.

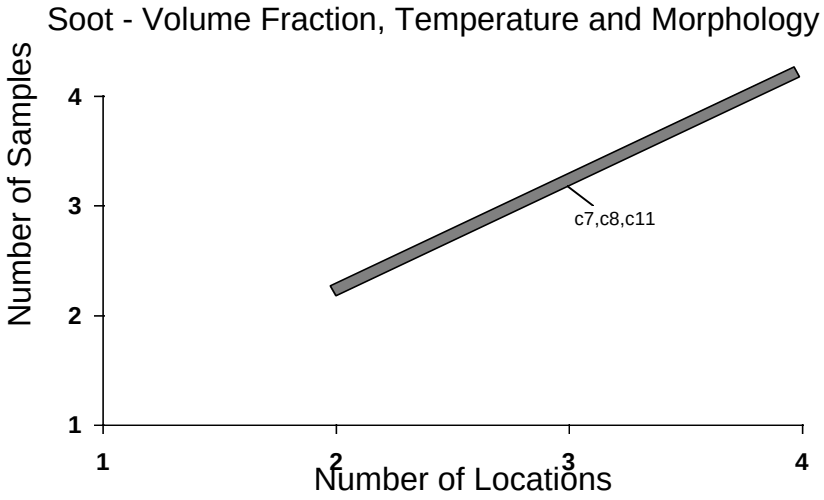
There is some overlap with the requirements on infrared imaging, since information on spatial distribution of concentrations of radiating species (including soot particles) may be inferred from such measurements.

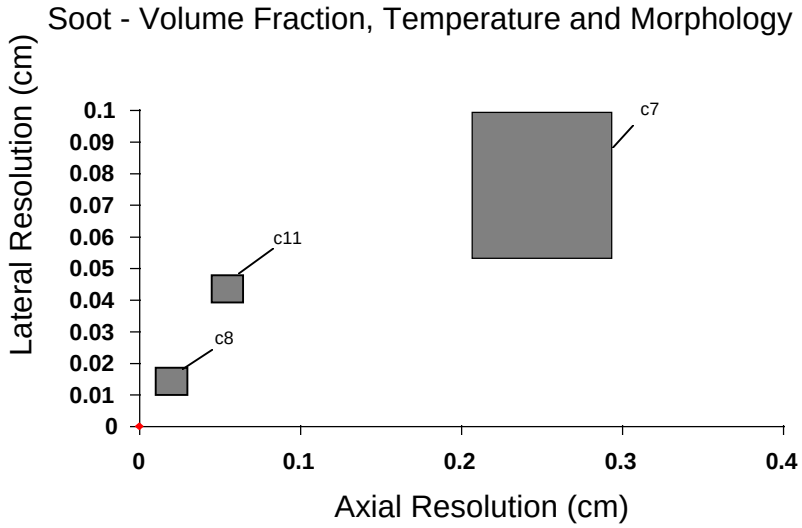
Soot measurements involve characterizing the soot volume fraction distribution, soot temperature, and soot morphology. Soot volume fraction distribution and soot temperature measurements are required to be non-intrusive. Soot morphology is obtained by study of soot particles obtained from intrusive sampling. Chemical composition measurements can also be used for determining temperatures.

Requirements on soot measurements and chemical composition are shown below in terms of: (1) field of view (lateral vs. axial) for the volume fraction and temperature measurements; (2) resolution (lateral vs. axial) for spatial resolution of the volume fraction and temperature measurements. In addition, for intrusive soot sampling, requirement on number of samples versus number of locations for collection are also shown.

Suggested Techniques: Thermophoretic soot sampling, two color pyrometry, infrared spectroscopic array, laser-induced incandescence, laser-induced fluorescence, light absorption, gas sampling, gas sensors, gas analysis with gas chromatography, and mass spectroscopy.

Facing figures show the range of parameters for number of samples, number of locations, axial resolution, and lateral resolution for soot measurements which define the envelope required to accommodate the basis experiments presented in this document. An additional figure is on the following pages.

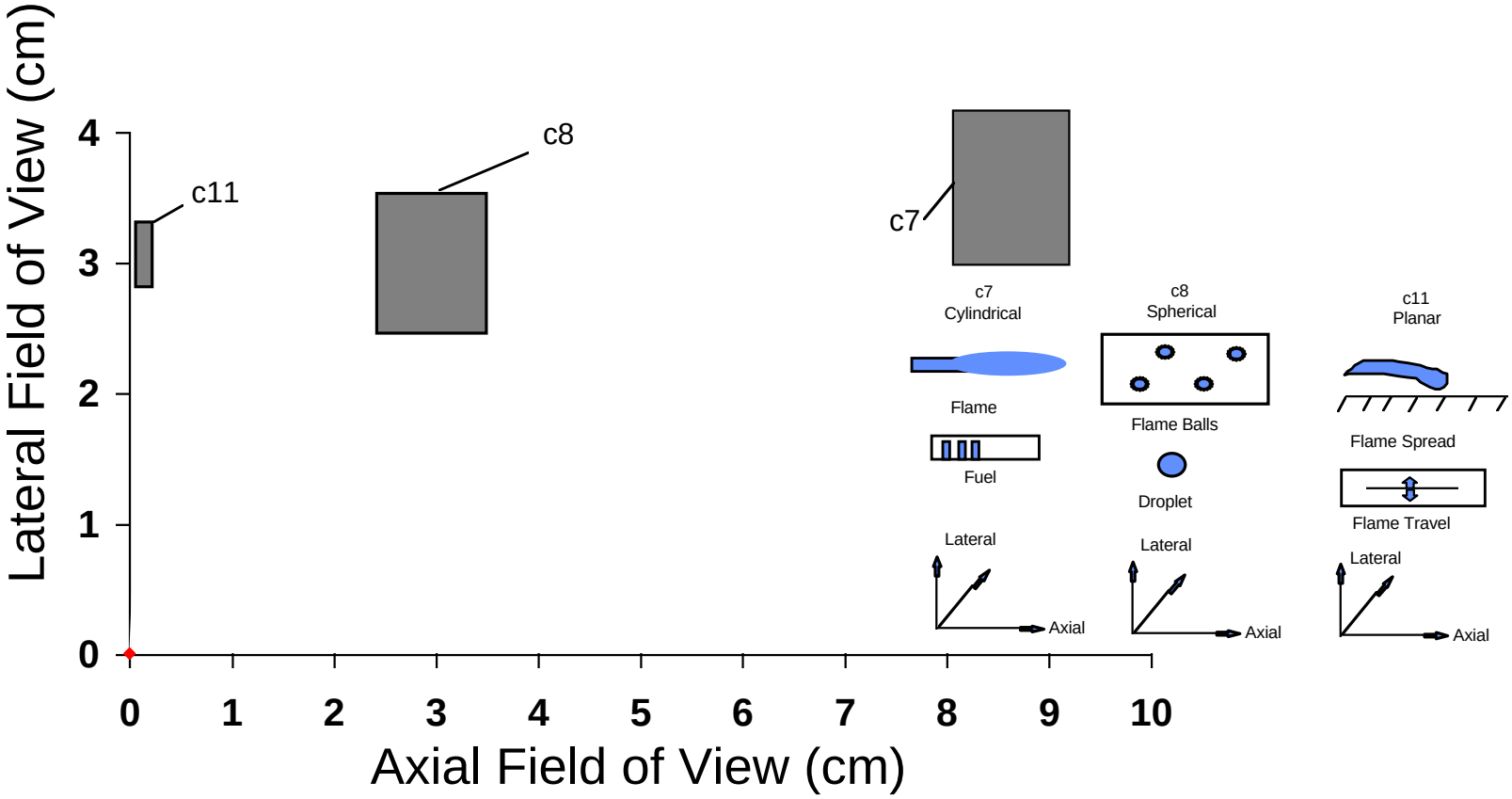

Soot - Volume Fraction, Temperature and Morphology
Number of Samples
4
3
2
1
c7,c8,c11
1
2
3
4
Number of Locations


Soot - Volume Fraction, Temperature and Morphology
Lateral Resolution (cm)
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
c7
c11
c8
0
0.1
0.2
0.3
0.4
Axial Resolution (cm)

Req. C14 - Chemical Composition (cont.)

Facing figure shows the distribution and range of parameters for lateral and axial field of view for soot measurement, which define the envelope required to accommodate the basis experiments presented in this document.

Soot - Volume Fraction, Temperature and Morphology



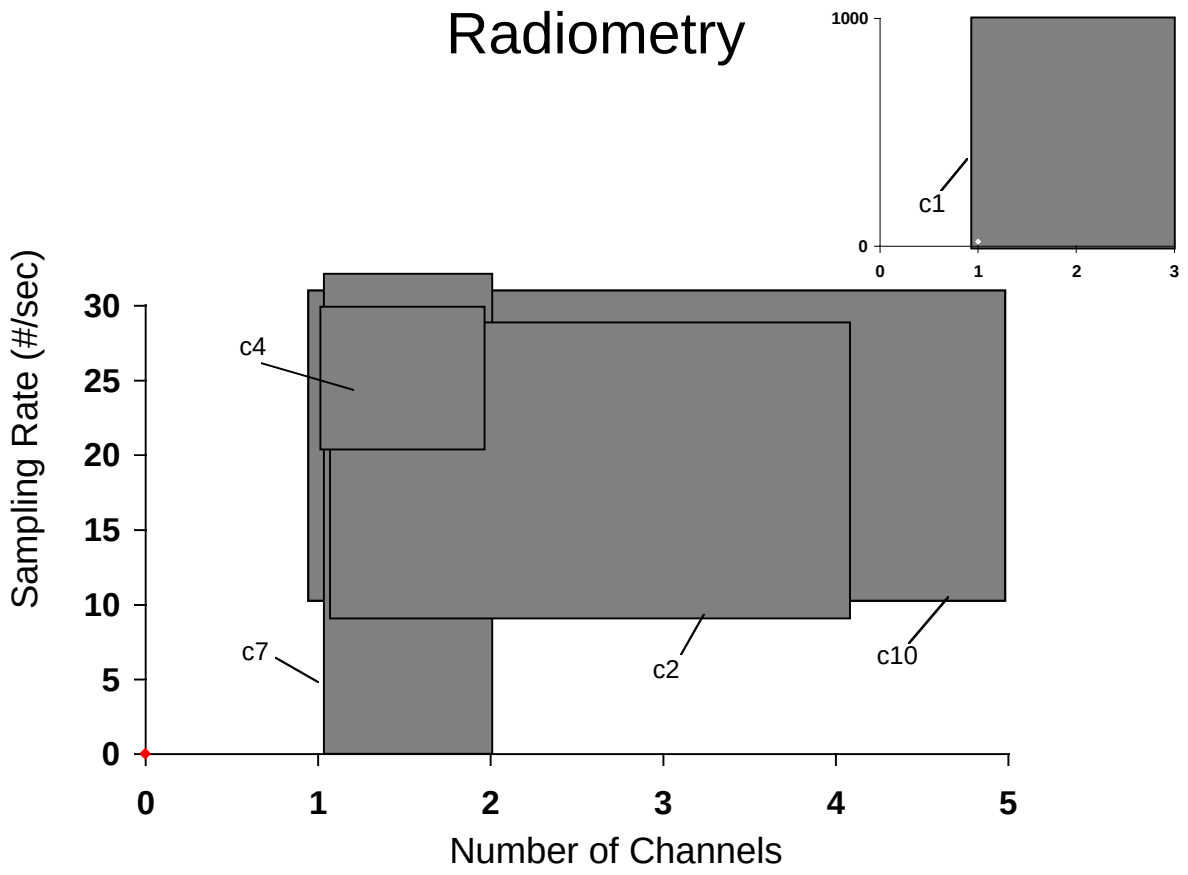
Req. C15 - Radiometry

The FCF shall provide power, control and data acquisition capabilities for measuring radiated energy in the spectral range 200 to 20,000 nm during the combustion experiment.

Radiometric measurements provide information on the thermal field and radiative losses from the combustion region. The typical wavelengths of interest are in the range of 0.2 to 20 microns. The field of view is variable with most experiments and the radiometric setup is expected to be integrated with experiment-specific assemblies.

Suggested Techniques: Radiometers, photodiodes.

Facing figure shows the distribution of number of sensors and sampling rates which define the envelope required to accommodate the basis experiments presented in this document.


Radiometry
1000
0
c1
0
1
2
3
Sampling Rate (#/sec)
30
25
20
15
10
5
0
c4
c7
c2
c10
0
1
2
3
4
5
Number of Channels

5.3.3 Evolution of the Fluid Dynamics

Req. C16 - Velocity Point Measurements

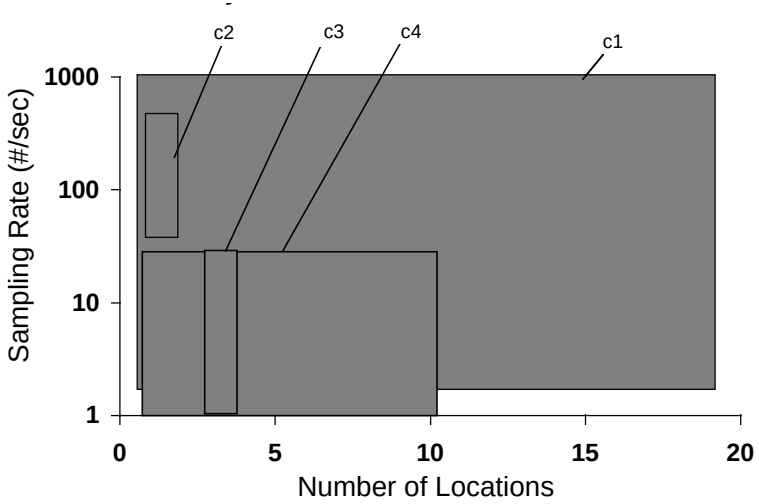
The FCF shall provide power, control and data acquisition capabilities for measurement of gas velocity in the test section over the range of 1 to 5,000 cm/second. Measurements shall be made at selected locations (1 to 20) in the test section and sampled at rates from 2 to 1,000 samples/ second.

Velocity measurements serve to verify the flow conditions of the experiment and also the velocities that are attained during the evolution of the combustion experiment.

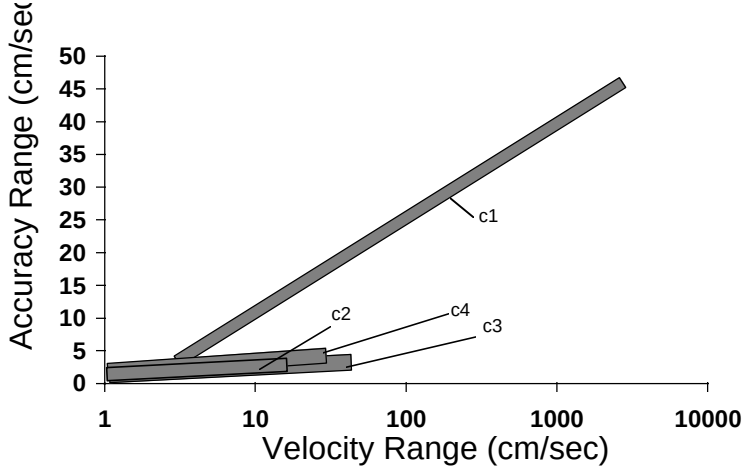
Suggested Techniques: Hot film and hot wire anemometers, pitot static probes, LDV.

Facing figures show the distribution of sensor count, sampling rates, velocity range and precision for velocity point measurements which define the envelopes required to accommodate the basis experiments presented in this document.

Velocity - Point Measurements



Velocity - Point Measurements



Req. C17 - Full Field Velocity Imaging

The FCF shall provide power, control and data acquisition capabilities for full field imaging of velocities in the gas and liquid phases. Measurements shall encompass the required fields of views and be imaged at rates of 30 to 60/ second.

These measurements provide information on the flow patterns that develop during the combustion event. The requirements are shown in terms of axial field of view, lateral field of view, and framing rate. It is to be noted that for a given experiment, more than one view (e.g., orthogonal views) may be required.

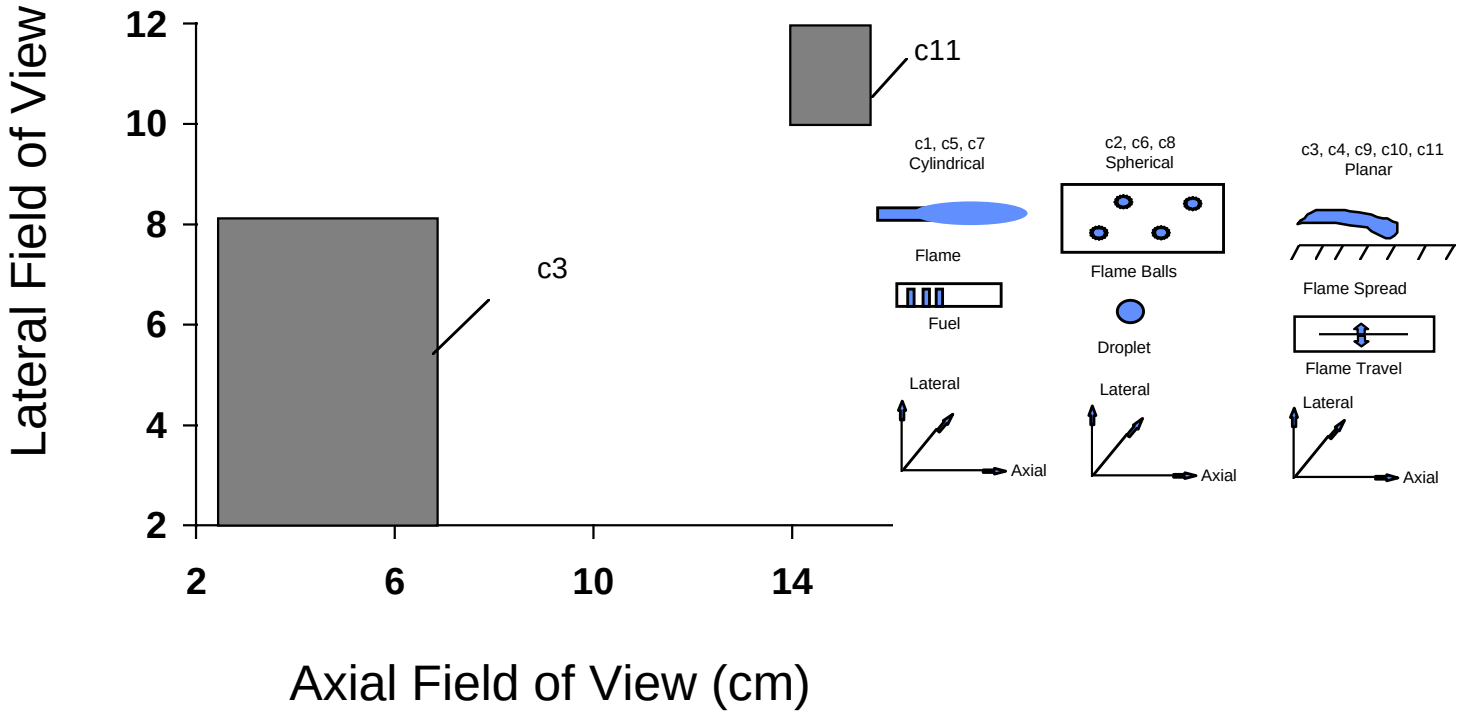
Des. DC8

It is desirable to accommodate imaging rates to 1,000/second.

Suggested Techniques: PIV, smoke trace visualization.

Facing figure shows the ranges of axial field of view, and lateral field of view, and framing rate, which defines the envelope required to accommodate the basis experiments presented in this document.

Full Field Velocity Imaging (frame rate 30-60)



Req. C18 - Acceleration Measurements

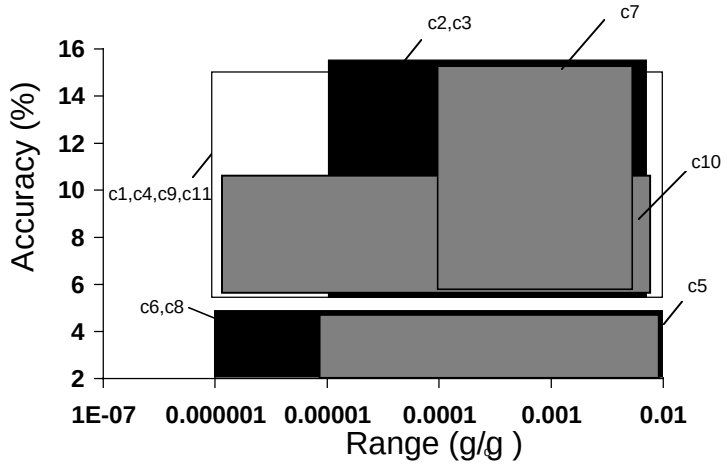
The FCF shall provide a capability to (typically) monitor residual acceleration and g-jitter over a dynamic range of 10^{-6} to 10^{-2} g/g_0 within the Combustion Facility rack. Specific requirements on frequency and levels will be called out in experiment-specific science requirements, but are expected to fall within the standard parameter range of the Space Acceleration Measurement System (SAMS) accelerometer system.

Acceleration measurements serve to verify the acceleration environment of the experiment. Measurements are to be made as close to the experiment as possible. Triaxial measurements are desired.

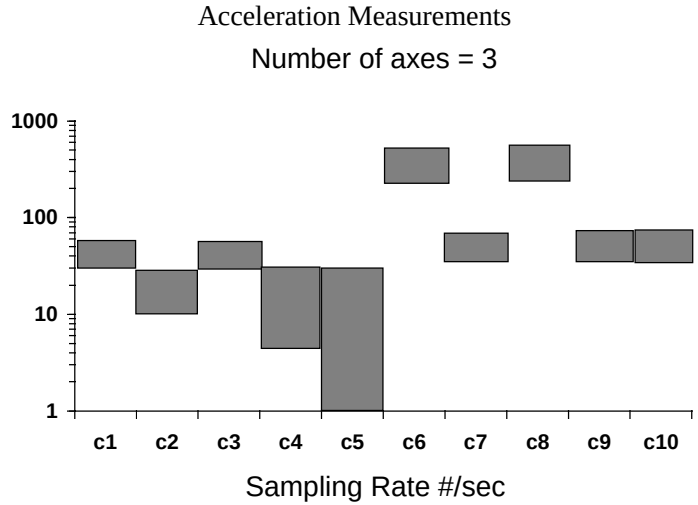
Suggested Techniques: SAMS.

Facing figures show the distribution of dynamic range, accuracy, and sampling rate which define the envelope required to accommodate the basis experiments presented in this document.

Acceleration Measurements



Acceleration Measurements



5.4 DATA MANAGEMENT

The requirements discussed in this section pertain to the acquisition and management of data acquired in the course of the experiment.

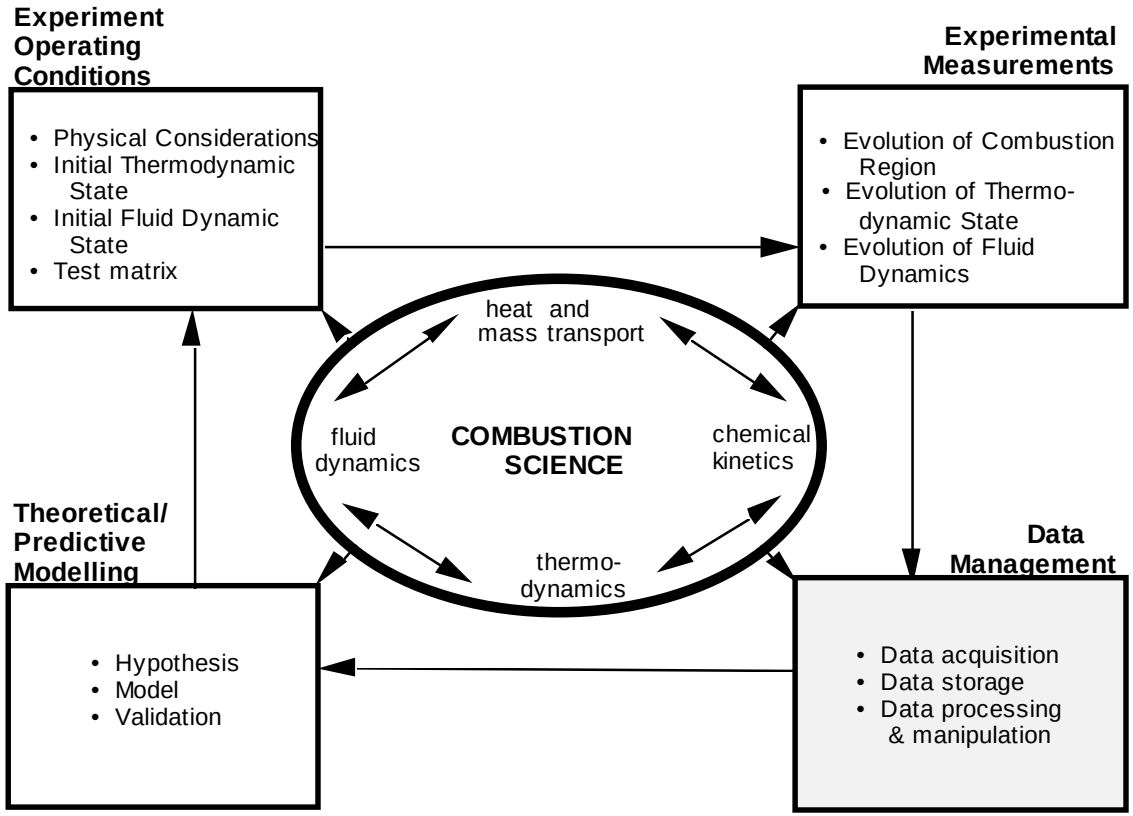
The following is a list of the requirements on data management.

*Note: Requirement numbers are prefixed with a capital C to indicate that it is a Combustion requirement. Small letter c's in the requirement pictures (i.e., c1 through c11) indicate the **c**ombustion basis experiment number.*

- Requirement C19 - Data Time Resolution

Facing figure illustrates the experimental process previously shown with Data Management highlighted (this Section 5.4). All requirements related to these conditions are in this section.

EXPERIMENT PROCESS MODEL



Req. C19 - Data Time Resolution

The FCF shall provide a capability to time-tag all data streams (including video data). A common clock (relatable to International Space Station events) shall be referenced and digital tags shall permit resolution to 1 second for external events and 0.001 second for experiment events..

Such a capability is required to permit the investigators to correlate a range of measurements within the experiment, as well as correlate experiment activities with external events, such as International Space Station maneuvers or crew activities.

Correlation of video data with other experiment measurements will be of particular importance. Ready identification of video segments for processing and downlink will also be facilitated by appropriate labels and tags.

(Note: There is no figure accompanying this page.)